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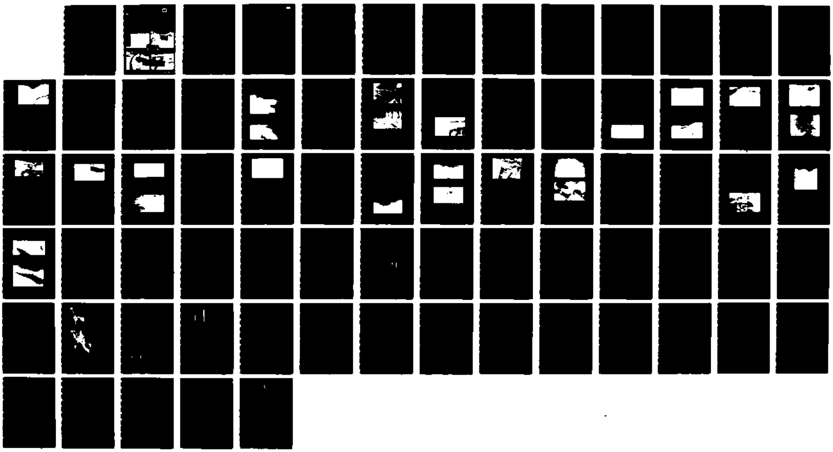

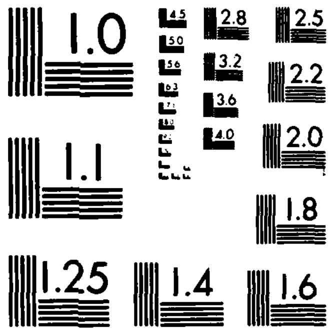

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Disturbance and recovery of arctic Alaskan tundra terrain
A review of recent investigations

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For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover (clockwise from upper left):

Thermokarst resulting from the 1949-1950 drilling operations at Oumalik Test Well No. 1. The pilings in the background were removed in 1980 along with other debris from the test well operations. (Photo by J. Ebersole, 12 Aug 1979.)

Natural thermal erosion caused by the melting of massive ground ice along a large lake near Oumalik Test Well No. 1. (Photo by J. Ebersole, 4 Aug 1979.)

Sprawl of the Prudhoe Bay Oil Field, with roads, construction camps and an oil well pad (left center). (Photo by D.A. Walker, Aug 1986.)

Thin gravel road and pad (right), with the Prudhoe Bay Spine Road curving from the bottom left. Note the thermokarst and the expression of ice-wedge polygon topography through the thin pad. (Photo by D.A. Walker, Aug 1978.)

CRREL Report 87-11

July 1987

Disturbance and recovery of arctic Alaskan tundra terrain
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D.A. Walker, D. Cate, J. Brown and C. Racine

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This document is a summary of over a decade of CRREL-managed research regarding disturbance and recovery in northern Alaska. Much of this research was sponsored by the U.S. Geological Survey's National Petroleum Reserve–Alaska exploration program and the Department of Energy's environmental research program, although numerous other agencies and members of the oil industry have also made contributions to several of the university participants. This work comes at a time of major transition in the focus of northern Alaskan environmental research from single-impact studies to analysis of cumulative impacts. Thus, it summarizes studies of anthropogenic disturbances in northern Alaska and discusses the immediate need for new methods to approach the problems of revegetation, restoration and cumulative impacts of terrain underlain by permafrost. This heritage of research comes from many research sites in northern Alaska, including Cape Thompson, the Seward Peninsula, Barrow, Fish Creek, Oumalik, East Oumalik, Prudhoe Bay, the Arctic National Wildlife Refuge and along the trans-Alaska pipeline. The impacts that are discussed include bladed trails, off-road vehicle trails, winter trails, ice roads, gravel pads and roads, borrow pits, roadside impoundments, road dust, hydrocarbon spills and seawater spills.

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The themes that are emphasized in this report are the following:

- Most anthropogenic disturbances have natural analogs, which can provide much inexpensive information that can be related to modern disturbances and their rates of recovery.
- 2) Most single-event disturbances will heal and develop a functioning ecosystem within a human life span, but a return to the original ecosystem can rarely be expected for major impacts.
- 3) The concept of recovery must be based on consistent terminology that recognizes the distinction between ecosystem resistance (the ability to withstand impact) and resilience (the ability to return to the previous undisturbed state) and also the distinction between complete recovery (a return to the original ecosystem) and functional recovery (the development of a functional ecosystem different from the original).
- In permafrost regions with massive ground ice, recovery of the vegetation is limited by alterations to the permafrost regime.

Synergistic and multiple-factor impacts are an increasing concern because of the likelihood of the development of additional oil fields across the North Slope and adjacent offshore regions. Research is needed regarding methods of assessing, predicting and mitigating cumulative impacts. Recommendations are presented for future directions in environmental research on arctic Alaskan terrain.

PREFACE

This report is a summary of research findings and conclusions based on CRREL-sponsored investigations and other research that has been initiated as a result of early CRREL funding. This work was conducted in northern Alaska between 1976 and 1983 and supported by the U.S. Geological Survey's National Petroleum Reserve-Alaska Program, the Department of Energy's Arctic Environmental Program, the U.S. Fish and Wildlife Alaska Investigations, the U.S. Environmental Protection Agency's Cold Climate Environmental Research Program, and several projects of the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL). Initial studies along the Dalton Highway were supported by the Federal Highway Administration (Brown and Berg 1980). The individual studies conducted under these projects have been and are being reported in CRREL reports, the open literature, and other forms of publication. They were conducted by CRREL investigators and university-CRREL contractors. The present report is a synthesis of many of the studies (listed in Appendix A) and our interpretation of knowledge already available in the literature.

Several drafts of the report were prepared in small workshops at CRREL (November 1982, 1983). The contributors include Gunars Abele, Jerry Brown, David Cate, Barbara Gartner (formerly of CRREL), Richard K. Haugen, Lawrence A. Johnson and Daniel E. Lawson of CRREL; James J. Ebersole, Vera Komárková, Donald A. Walker and Patrick J. Webber of the Institute of Arctic and Alpine Research, University of Colorado; K.R. Everett, Institute of Polar Studies, Ohio State University; Albert W. Johnson, San Diego State University; David F. Murray and Barbara M. Murray, University of Alaska Museum; F. Stuart Chapin, Institute of Arctic Biology, University of Alaska; Gaius R. Shaver, Marine Biology Laboratory; and Charles Racine. These investigators were managed by J. Brown, former Chief, Earth Sciences Branch, CRREL. The final writing and rewriting was handled by a small group who are listed as the editors of this report. Some investigators did not participate in the workshops but had an opportunity to contribute, review and add to the report in various stages of review. The report was formally reviewed by Fred Crory, whose several northern Alaska CRREL projects also provided financial support for the preparation of this report; Max C. Brewer, U.S. Geological Survey, Anchorage, Alaska; and John Schindler, Minerals Management Service, Bureau of Land Management.

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INTRODUCTION

Background*

The response and recovery of permafrost terrain following disturbances has been a major topic of scientific research in northern Alaska for the past 25 years. This interest was spawned by wide-ranging environmental concerns and the growing needs of industry for sound environmental information on minimizing impacts to tundra ecosystems. Between 1976 and 1983 many environmental research studies were conducted in northern Alaska by CRREL and its university collaborators. These investigations were performed primarily under the auspices of the U.S. Geological Survey's National Petroleum Reserve–Alaska (NPR-A) exploration program (Gryc 1985) and the Department of Energy's environmental research program. The goals of the research were to document natural and human-induced disturbances on Alaskan tundra and to investigate responses of tundra ecosystems to these disturbances. The results should serve as an important aid for preparing environmental impact assessments and statements and developing recommendations and procedures for resource management of tundra regions.

Multidisciplinary studies such as those reported here evolved from a considerable heritage of basic environmental research beginning in 1959 with the Atomic Energy Commission's (AEC) studies at Cape Thompson (Wilimovsky and Wolfe 1966). Those studies and the ecological research emanating from the Naval Arctic Research Laboratory at Barrow established the general characteristics of the plants, animals, soils, climate and permafrost (Britton 1973). In the early 1970s the National Science Foundation's International Biological Program (IBP) Tundra Biome program at Barrow (Brown et al. 1980) and Research on Arctic Tundra Environments (RATE) program at Atkasook (Batzli and Brown 1976, Batzli 1980) continued the basic research on tundra ecology. Studies of the response of arctic tundra to human-induced disturbances began in the late 1960s, just prior to the IBP programs in Canada and Alaska, and were associated with the renewed oil exploration and discovery (Bliss et al. 1970, Fuller and Kevan 1970, Bliss and Wein 1972a, b). In Alaska, research on disturbances included experimental studies at Barrow, at Prudhoe Bay (Walker et al. 1977, 1978, Abele et al. 1978, 1984, Simmons et al. 1980) and along the Dalton Highway north of the Brooks Range (Brown and Berg 1980). Many NPR-A sites that had been disturbed by gas and oil exploration activities between 1944 and 1953 were revisited, and the recovery of the disturbed tundra was documented (Lawson et al. 1978, Lawson and Brown 1979, Lawson 1982, Ebersole 1985). Sites at Cape Thompson disturbed during the AEC studies between 1958 and 1962 were also re-examined (Everett et al. 1985). Appendix A contains a list of projects that were funded by our efforts and that contributed to this report.

It is now possible to evaluate tundra recovery rates and patterns over a span of 20–30 years for a variety of sites in the Arctic Coastal Plain and the Arctic Foothills. Information and understanding of the tundra dynamics of northern Alaska gathered during this research contributed to numerous environmental assessments and environmental impact statements for the NPR-A (Department of the Navy 1977, U.S.Geological Survey 1979, National Petroleum Reserve in Alaska Task Force 1979), the Waterflood Project at Prudhoe Bay (U.S. Army Corps of Engineers 1982) and the Arctic National Wildlife Refuge (ANWR) (U.S. Department of Interior 1983).

* Prepared by J. Brown.

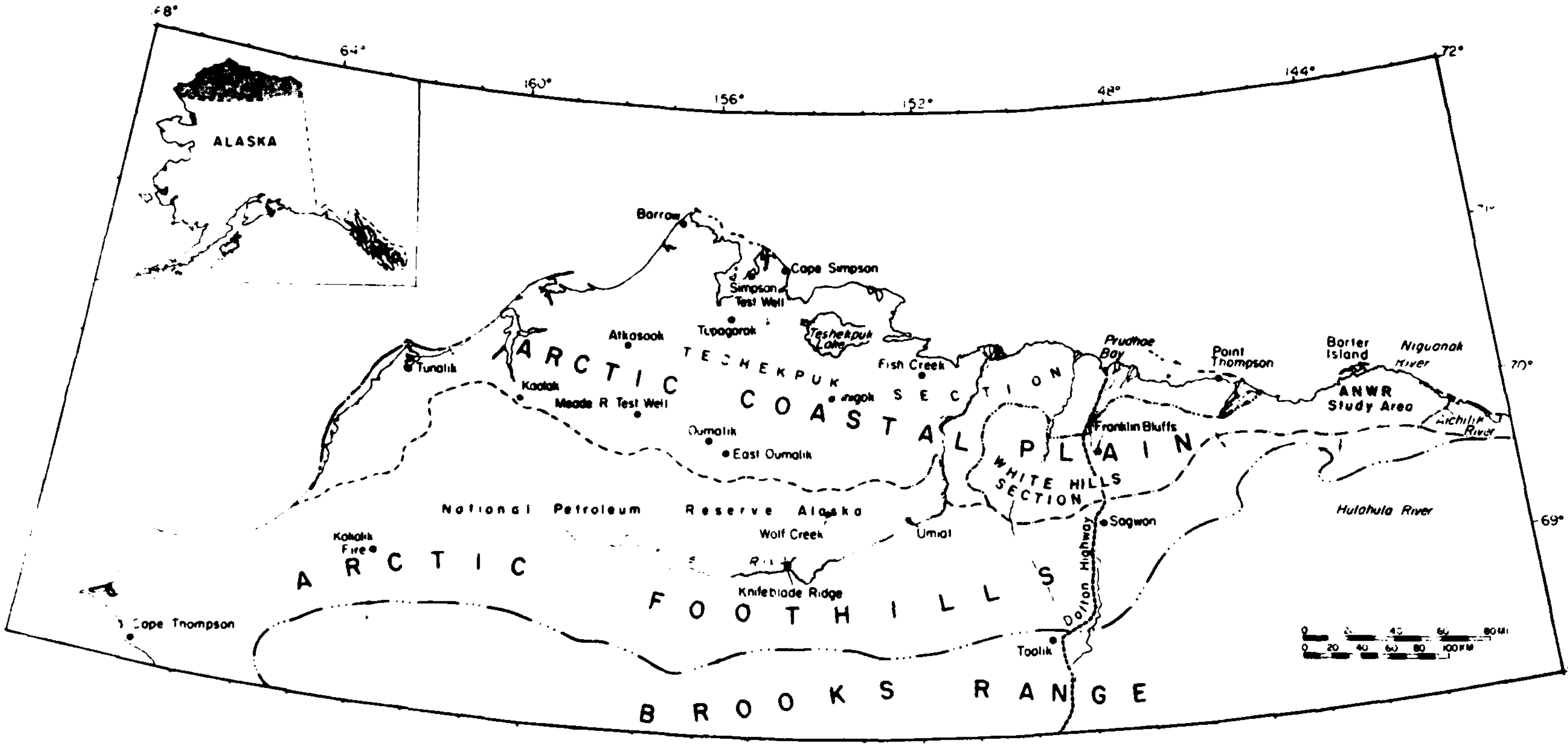


Figure 1. Northern Alaska and the place names used in this report.

A wide range of tundra disturbances have been documented in northern Alaska. Some were natural events, such as frost action, fire, river and shore erosion, and thaw-lake drainage and formation; others were human-induced, such as off-road vehicle trails, bulldozed trails, road and drill pad construction, and hydrocarbon and seawater spills. Observations at these disturbances and sites of recent reclamation efforts along the Alyeska Trans-Alaska Pipeline System (TAPS) and in NPR-A have led to new concepts regarding arctic terrain sensitivity and recovery following disturbance.

Revegetation and restoration of Alaskan tundra ecosystems have a heritage of little more than a decade. Most methods for revegetation were developed as part of the construction and maintenance of the trans-Alaska pipeline; some of these techniques were costly to initiate and maintain. Different approaches might have evolved if we had better understood the processes and rates of natural revegetation and the courses of natural adjustments to thermally or mechanically disturbed tundra. Particularly valuable insights into restoration have come from the sites disturbed 20–30 years ago that have had no additional disturbances since the initial impacts.

Many of the severe impacts that occurred 20–30 years ago are not likely to recur because of new regulations and the early recognition by industry of the problems involved with disturbing permafrost terrain. Most of the past disturbances were caused by single events and were left to recover after a relatively short period of disturbance. Future disturbances are likely to be less intense but occur repeatedly over longer time periods. Thus the major questions now are related to cumulative impact, which is defined here as the total current and future interactive impacts on the terrain and wildlife habitats (Horak et al. 1983). For example, what is the pattern of oil-field expansion and modification of the surrounding land? What will be the ultimate effect of the developing array of roads and pipelines? And are the impacts synergistic? Currently there are no theories of cumulative impact that can be applied with confidence. It is apparent that there is a need for comprehensive planning methods that will minimize cumulative impacts. Thus, one goal of this document is to summarize what is known regarding disturbance and recovery in arctic Alaska and to discuss methods and approaches that are available to assess potential cumulative impacts.

The report consists of three major sections. The first section, the introduction, contains a brief regional description and a discussion of some of the ecological concepts related to terrain disturbance and recovery. The second section is a summary of CRREL-sponsored studies at old disturbances in NPR-A and Cape Thompson plus information from recent disturbances associated with the Prudhoe Bay oil field and the Dalton Highway; it is divided into natural disturbances and anthropogenic (human-induced) disturbances. The final part is titled "Toward an ecological understanding of disturbance and recovery in arctic tundra ecosystems." It consists of four sections: physical recovery, vegetation recovery, cumulative impacts, and the future directions for arctic disturbance ecology research.

Regional description*

Arctic ecosystems range widely, in both their structure and their response to disturbances. In northern Alaska these ecosystems are distributed along a 200-km-long north-south climatic gradient that includes changes in elevation of over 2000 m. The biotic and environmental diversity associated with various gradients was incorporated into the research through observations at a large number of sites (Fig. 1).

Physiographically, northern Alaska is divided into three distinct provinces (Wahrhaftig 1965). The northern region, the Arctic Coastal Plain Province, is gently rolling or nearly flat and dotted with small ponds, shallow thaw lakes, and drained lake basins. The Foothills Province is hilly and better drained, with much less standing water. Both the coastal plain and the foothills have nearly continuous vegetation cover. The mountainous southern province is the Brooks Range, where the higher elevations have steep, rocky or gravelly slopes and discontinuous or patchy vegetation cover. All three physiographic provinces include large rivers that are meandering or braided. The region from the continental divide of the Brooks Range to the arctic coast is commonly referred to as the North Slope. Each province includes a number of geologically distinct substrates (Fig. 2). For example, a large area of the coastal plain in NPR-A is covered by sand dunes (Black 1951, Carter and Hopkins 1982). The soils and vegetation of this area contrast markedly with the coastal areas of marine silts and the eastern parts of the coastal plain, which consist of gravelly glaciofluvial outwash.

The climate of the region is cool and relatively dry (140–267 mm of precipitation annually).

* Prepared by V. Komárková and D.A. Walker.

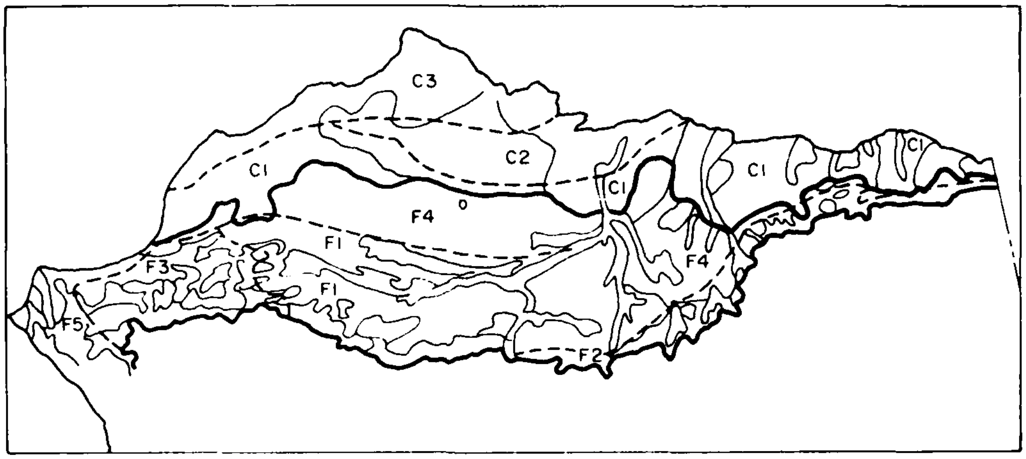


Figure 2. Major soil regions of Alaska's Arctic Slope. The heavy solid lines delimit Coastal Plain and Foothill Provinces (Rieger et al. 1979). The dashed lines define the major tundra soil patterns of northern Alaska, as recognized by Tedrow and Brown (1967). These are designated by letter-number combinations as follows. C—coastal plain: 1-sandy and fine sandy loams, 2-sands, 3-loams, silt loams and organics. F—foothills: 1-silt loams, 2-stony loams, 3-loams on steep topography, 4-fine sands, 5-loams with dark sola. The fine solid lines delimit soil boundaries from the Exploratory Soil Survey of Alaska *(Rieger et al. 1979). Base from* National Atlas, Northern Alaska *(U.S. Geological Survey 1976). (From Everett and Brown 1982.)*

Along the Dalton Highway the mean annual temperatures range from -9.0° to -11.1°C in the foothills, and from -10.6° to -12.8°C on the coastal plain (Haugen 1979, 1982, Haugen et al. 1983). The summer thaw period lasts only about 90 days. Although the total amounts are roughly equal across the coastal plain, precipitation is more frequent near the coast and often occurs in trace amounts. Short, high-intensity convective storms are common in summer in the foothills and mountains.

On the coastal plain the measured permafrost thickness ranges from about 180 m at Fish Creek (Lawson 1982) to 650 m at Prudhoe Bay (Gold and Lachenbruch 1973). In the foothills, thicknesses are less (170–300 m). Ground ice is common in the unconsolidated sediments. On the coastal plain near Barrow, massive ground ice is mainly concentrated in the upper 10 m or so of the surface, where it may account for 10% to over 70% of the ground by volume (Sellmann et al. 1975). Ground ice is a major ecological concern in most areas of northern Alaska. Often it is necessary to take steps to prevent its melting in construction areas; otherwise, major, irreversible changes in the landscape are likely to occur. Massive ground ice (Fig. 3) in the form of ice wedges and lenses is common throughout the region. Often the surface pattern provides a clue to the presence and types of ground ice; for example, beneath portions of the highly polygonized coastal plain, ice wedges may account for more than 45% of the volume in the upper 3-5 m. The northernmost foothills contain large amounts of ground ice (e.g. Lawson 1983b), while in the more southerly glaciated parts, ice is apparently less common. In all cases, ground ice distribution and content are poorly known (Lawson 1986).

Because of the short thaw period, the low summer temperatures and the insulating properties of the organic surface soil, the seasonal thaw ranges from less than 0.5 m in wet, fine-grained coastal plain sediments to generally less than 1.0 m in the coarser materials of the foothills (Fig. 2). Some coarse-textured materials of well-drained sites and stream valley deposits may thaw to 1.5 m.

The vegetation of northern Alaska shows a pronounced zonation with latitude (Cantlon 1961). A narrow strip of coastal tundra that Cantlon designated "littoral tundra" is dominated by sedges, grasses, mosses and dwarf shrubs but lacks many of the woody plants, forbs and lichens that are common farther inland. Tussock tundra dominated by *Eriophorum vaginatum* is also poorly developed in this strip. Inland portions of the coastal plain are dominated by sedge and moss communities in wet sites and tussock-sedge communities with dwarf shrubs, mosses and lichens in moist sites. Dry, elevated habitats, such as ridges and pingos, are occupied by a greater proportion of

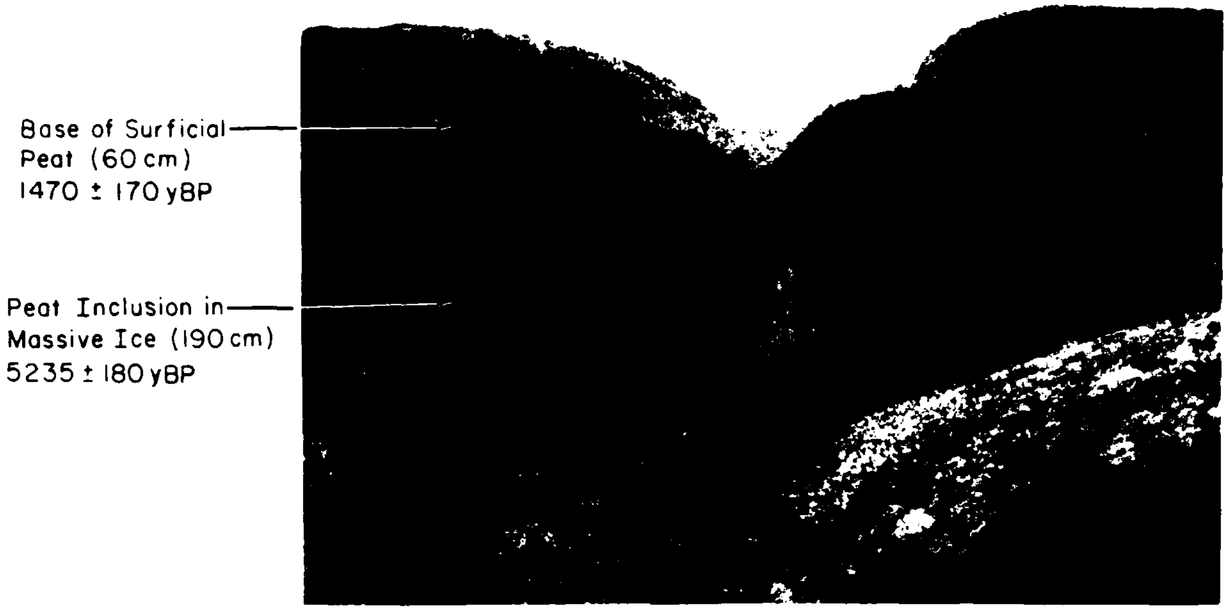


Figure 3. Massive ground ice exposed along the Sagavanirktok River near Deadhorse. The ice wedge in the center of the photo lies beneath a high-centered polygon trough. The massive ice beneath the polygons has numerous peat inclusions, one of which was dated by ^{14}C. (Photo by D.A. Walker.)

dwarf shrubs, mat and cushion plants, and lichens. The foothills are dominated by tussock-sedge, mixed-shrub tundra. Well-developed willow communities occur along foothill streams. The east-west vegetation gradient is not as distinct and appears to be partially related to a more maritime climate in the southwestern part of the North Slope. Another major influence on the vegetation is associated with calcareous loess, which covers a large portion of the central Arctic Coastal Plain, primarily between the Sagavanirktok and Colville rivers. Distinct tundra types that are dominated by either acidophilic or calciphilic plants are related to the patterns of loess distribution (Walker 1985).

The vegetation varies dramatically along short mesotopographic gradients. Flood plains, especially of the larger streams, have a diverse and complex vegetation including prostrate shrub areas, barren gravel bars, willow thickets and snowbank communities along the marginal bluffs. There are areas of active sand dunes, particularly in the sand region of NPR-A (Carter and Hopkins 1982), as well as in the delta regions of some large rivers and on river bars. Microtopographic gradients associated with frost scars, ice-wedge polygons, palsas and pingos cause distinct local vegetation patterns. Detailed plant community studies at the widely separated sites of Barrow, Oumalik, Fish Creek, Atkasook and Prudhoe Bay have shown that while the basic appearance of the tundra was predictable across the coastal plain, each site had a unique suite of vegetation types and plant species that was not predictable based on previous knowledge. This points to the need for continued detailed analyses at sites of proposed development.

Concepts of disturbance and recovery*

The imprecise and varied use of terms relating to tundra ecosystem dynamics has led to confusion among both scientists and resource managers. Disagreements abound on the nature of tundra recovery from impact. At the outset it is essential to recognize the interconnectedness of the physical and biological components of the ecosystem. In this report we emphasize the importance of stabilizing the physical system (permafrost and soils) before the biological components can stabilize. The following definitions are provided for the terms used in this report.

Disturbance is a factor that displaces the natural system, such as vegetation or its substrate, beyond its normal limits of variation (White 1979). It is thus an element that causes a change to the terrain. We distinguish disturbances caused by humans as *anthropogenic* disturbances and consider all others as *natural* disturbances. A disturbance is

* Prepared by P.J. Webber and D.A. Walker.

generally considered to be destructive, although in some instances a more biologically productive or diverse ecosystem may result; this happens, for example, when bulldozing of tussock tundra or stream eutrophication due to pollution results in new or more productive shrub communities.

Ecological systems are both *resistant* and *resilient*. *Resistance* is the ability of the system to withstand disturbance without changing its initial state. In a vegetation context, change refers primarily to community composition or productivity. *Resilience* is the ability of a system to return toward its original state once a change has occurred (Vitousek et al. 1981). At the *resistance threshold* the ecosystem is no longer resistant to disturbance and changes in composition or productivity occur. At the *resilience threshold* the ecosystem is no longer able to return to its original state.

Central to these concepts is that of *recovery*, which we define as the process by which an ecosystem achieves relative biological and physical stability following a disturbance. The final stage of recovery is a healthy, functioning ecosystem that can maintain a steady-state equilibrium over a few decades. Conceptually it is similar to the successional process, which leads ultimately to some form of climax vegetation (Clements 1928). Although recovery may involve several successive steps, it does not necessarily result in a climatic climax or even a plant community similar to one that previously existed. But it does result in a stable, healthy functioning ecosystem free of polluting or continuously disruptive influences. Recovery is a pragmatic term that is useful in terms of human life spans.

When a disturbance changes the original ecosystem beyond its resilience threshold, for example by altering its topography or substrate, the new vegetation community will always be different in some way (productivity, floristics or structure) from the original. The degree of difference will depend upon the degree of change. For the purposes of this report, there are four states of recovery and one state of nonrecovery (Fig. 4). *Functional recovery* occurs when an ecosystem has been permanently or severely altered but has recovered to a point where it is a stable, functioning ecosystem. Functional recovery may have either greater vegetation productivity (*positive functional recovery*) or less productivity (*negative functional recovery*), depending on how the substrate has been altered. *Complete recovery* occurs only when the ecosystem has regained its original productivity and species composition. A vegetation type may have no possibility of returning to its original state because the prevailing climate has changed since the original community formed or because the set of conditions leading to the original community cannot be repeated (Webber and Ives 1978, Komárková and Webber 1978). The recovered tundra, then, may be either the same or different from its original state, but it provides surface integrity and a

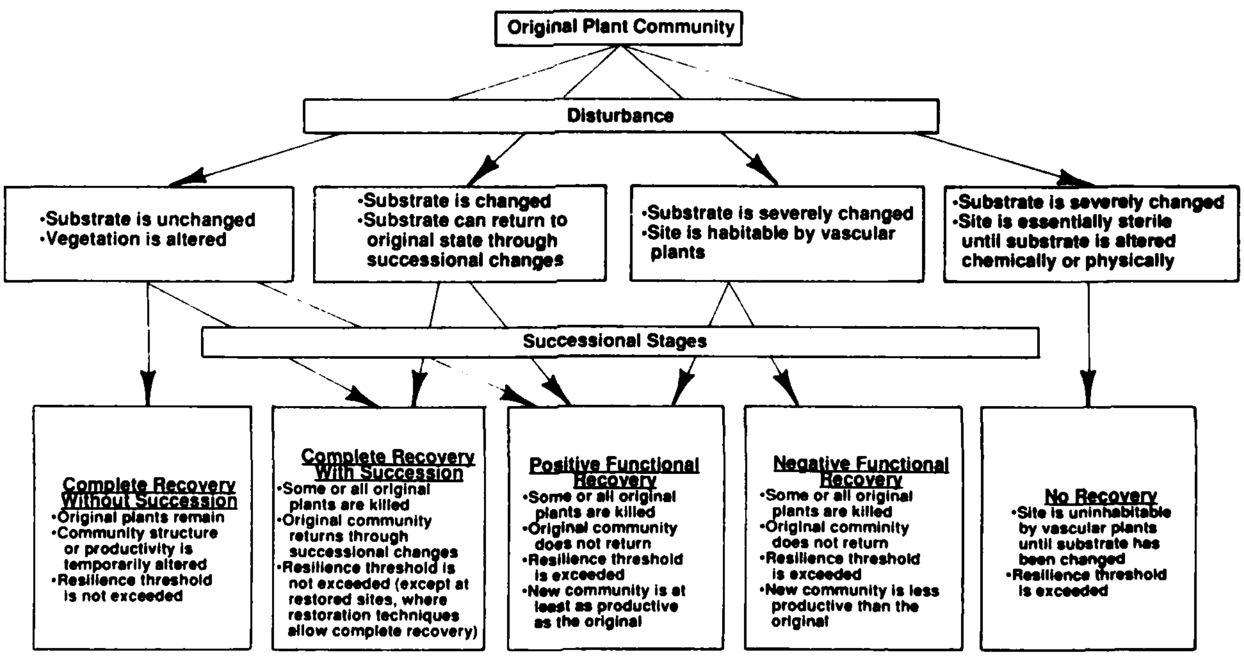


Figure 4. Pathways of recovery following disturbance.

primary base of vegetation to support consumer organisms. The advantages of this concept of recovery are that it relates the recovery of an ecosystem to the original as a function of species diversity and productivity, and that it emphasizes a human time scale.

When recovery is affected by management procedures, the terms revegetation and restoration are frequently used. *Revegetation* is the introduction of a plant cover to a severely disturbed, often barren, site. The new vegetation is often quite different from the original. *Restoration* is the attempt to return the site to its former natural state. Successful restoration would result in complete recovery as shown in Figure 4.

The distinction between complete recovery and functional recovery has implications for management decisions. Most revegetation and restoration policies regard an ecosystem as legally revegetated when the vegetation attains a percentage of vegetation cover close to that of its predisturbed state (e.g. U.S. Department of Interior 1977, 1982). This may be a desirable concept in some areas, but others (for example, wilderness areas) may require a more rigorous concept, one that specifies a return to the original floristic composition as well as the original plant cover and productivity. Prior to exploration or development, it would be desirable to define what type of recovery is acceptable in a given area, and then permit only activities from which that type can be achieved either naturally or through active measures that assure recovery in an acceptable time.

DISTURBANCE TYPES

Natural disturbances

Perennially frozen terrain is disturbed by a variety of natural processes. In northern Alaska these processes include thaw-lake erosion and expansion, streambank erosion and associated valley slope failures, freeze–thaw processes and frost heaving, coastal and shore zone processes, animal activity and fire. They often alter the thermal state of the material and induce thawing and degradation of the terrain. The magnitude of change resulting from both natural and human-caused disturbances depends mainly on the quantity, distribution and dimensions of ground ice (Mackay 1970), but the response at any location also depends on the relief, the sediment, the vegetative cover, the local climate, and the chemical and edaphic changes caused by the disturbance.

Many anthropogenic disturbances have natural analogs that can be studied to help understand the response of physical and biological systems (Table 1). For example, by knowing the local processes and successional patterns associated with thaw-lake formation and drainage, we can more accurately predict the sequence of events associated with impoundments caused by roads. In nearly every instance, though, there is some characteristic of a human-induced disturbance that keeps it from being fully comparable to its natural analog. In our example, road-induced impoundments form rapidly when a natural drainage is blocked; thaw lakes form gradually. Also, most road-in-

Table 1. Natural analogs of anthropogenic disturbances.

Human-caused disturbance	*Natural analog*
gravel road, runway and pad surfaces	gravel river bars
dust from roads	loess from rivers
impoundments	thaw pond subsidence
thermokarst	natural thermokarst
brine spills	ocean storm surges
crude oil spills	oil seeps
bladed trails	slope failure, river and lake banks, frost scars
berms of bladed trails	ice-pushed turf
summer off-road vehicles	caribou trails
solid waste	ice-pushed boulders, driftwood from storm surges
material sites	gravel river bars
fire	fire
winter trails, snow roads, ice roads	aufeis, snowbeds

duced impoundments drain at least partially during the summer after the ice in culverts melts out. Natural disturbances often differ in their rate and extent of formation, and thus are not often perfect analogs for anthropogenic disturbances. Many anthropogenic disturbances, in fact, have no good natural analogs. Examples include spills of refined hydrocarbons and other highly toxic substances.

This should not, however, dissuade investigators from examining natural disturbances as a major element in the study of anthropogenic disturbance. Controlled experiments on the response of physical and biological systems are extraordinarily difficult and expensive because of the large number of variables involved. Observations of natural disturbances can provide knowledge of the plants and mechanisms involved in natural succession and thus greatly reduce the amount of experimentation required to understand recovery. The following discussion summarizes some important natural disturbances that have been studied in the course of CRREL-sponsored research on the Arctic Coastal Plain. Other natural disturbances, such as landslides and slope failures, aufeis, river bars, sand dunes, oil seeps, and modern-day loess deposition, are not discussed here but also have significance with regard to development-related disturbances.

*Thaw lakes and thermokarst**

The process of formation, expansion and destruction of shallow lakes on the coastal plain of Alaska has been termed the thaw-lake cycle (Hopkins 1949, Britton 1957). Britton (1957) hypothesized that a successional sequence exists in conjunction with thaw lakes. Since the time of his work, this cycle has been considered a primary force in shaping the landscape of the Arctic Coastal Plain. During the late 1950s and 1960s, numerous theories were developed regarding the formation of thaw lakes and their apparent elongation with respect to the prevailing northeasterly winds (e.g. Rex 1960, Carson and Hussey 1962). Although the cycle is frequently mentioned today, there is still little quantitative information regarding the processes and time scales involved.

The patterns of vegetation succession in drained thaw lakes are affected by the substrate, the local climate and the manner of drainage. For example, a thaw lake that drains rapidly exposing a mineral lake bottom will likely create a very dry habitat that will be slow to revegetate, whereas slow incremental drainage often creates an intricate complex of ponds and strangmoor that become vegetated with *Arctophila fulva* followed by *Carex aquatilis* and eventually species typical of moist sedge, dwarf-shrub tundra. The latter sequence is a typical hydrarch succession, described by Billings and Peterson (1980) at Barrow, where lake bottoms are often covered by detrital or reworked peat. The sequence at Barrow, however, is not representative of all the coastal plain, particularly in areas that have sandy lake bottoms and in the southern part of the region, where the climate is warmer, and willows, alders, *Sphagnum* and a greater variety of aquatic taxa are important. Pond processes in the alkaline portions of the coastal plain have not been studied with nearly the detail of those in acidic areas (Hobbie 1980, 1984).

Thaw lakes have likely been a major agent of landscape modification throughout the Holocene, although the degree of activity has varied greatly due to climatic fluctuations (Black and Barksdale 1949, Brown 1965, Carter 1981a,b, 1983, Hopkins 1982). Historical accounts of lake succession are not well known. Studies at Fish Creek and Oumalik (Lawson 1983b and unpub.) suggest that the presently active thaw lakes are a recent phenomenon; 36,000 to 40,000 years ago the lakes did not exist, and much of northern Alaska was extremely dry with little surface water. Within the last 14,000 years, three periods of widespread thaw-lake development may have occurred (Carter et al. 1984).

Although portions of the process of thaw-lake formation, degeneration and vegetation succession have been documented, the mechanism that triggers the initiation of the lakes, the processes by which they expand and become oriented, and even the existence of a cycle are still in question. The answers to these questions have important applications for understanding processes related to anthropogenically flooded tundra. An understanding of vegetation succession, both during the formation of lakes and after lake drainage, is important for properly managing coastal wetlands in areas of development.

*Streambank erosion**

Streams can physically disturb permafrost terrain, particularly during high discharges and flooding. Thermal erosion results when warmer water flows over frozen beds or adjacent to bank materials. Melting ice within the banks leads to thaw settlement and increases the erodibility of the

* Prepared by K.R. Everett and D.E. Lawson.

* Prepared by D.E. Lawson.

materials by reducing their shear strength. The processes associated with natural streambank erosion are analogous to situations where thermal erosion has been induced by off-road vehicle movement or by construction, such as may occur when meltwater is channeled along the edges of roads and through culverts (Mackay 1970, French 1974, Lawson and Brown 1979, Berg 1980, Lawson 1982).

Eroding banks in permafrost, whether along streams or lakes, are typically characterized by thermoerosional niches (e.g. Williams 1952, Abramov 1957, Walker and Morgan 1964, Miles 1977, Scott 1978, Walker 1983) (Fig. 5). These niches result from thermal and mechanical erosion and undercutting of banks by currents and waves. They extend laterally into bank sediments, which eventually collapse into the river (Fig. 6). Niches

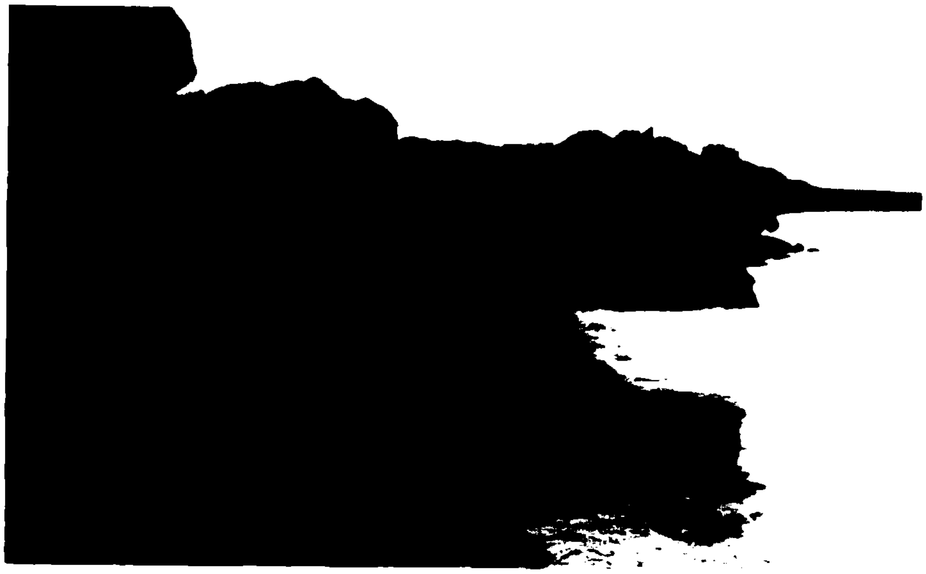


Figure 5. Thermoerosional niche in massive ice adjacent to the Sagavanirktok River near Deadhorse. The niche extends approximately 7 m horizontally beneath the ice face in the foreground. (Photo by D.A. Walker, 10 Aug 1984.)

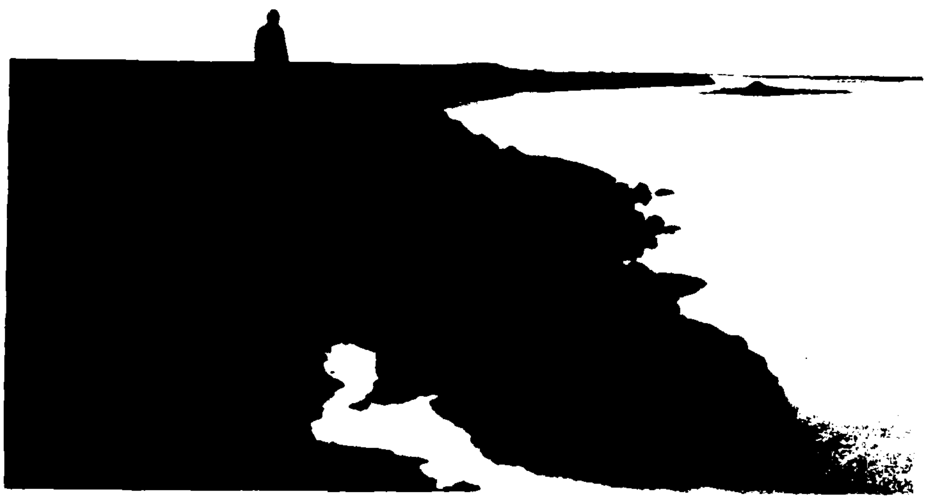


Figure 6. Collapsed blocks of tundra near the site shown in Figure 5. (Photo by D.A. Walker, 10 Aug 1984.)

can be more than 10 m deep. Thawing sediments on lower-angle slopes may also fail due to loss of strength resulting from the addition of meltwater or the generation of excess pore pressures. Blocks of material may either slip along the surface at the base of the active layer or flow downslope as a saturated mass.

The area of thaw will expand faster into bank sediments with high ice contents and especially ice wedges (Ritchie and Walker 1974). Ice wedges exposed by riverbank erosion melt faster than adjacent frozen sediments, developing small gullies within the bank face. The faces of ice wedges or other massive ice bodies may act as planes of weakness along which slip failures may take place (Harper 1978). This in turn exposes additional frozen sediments within the gully walls to thawing and subsequent thaw subsidence and failure. Meltwater channeled within these gullies transports thawed sediments into the streams as well as inducing further thermal erosion. Overland sheet flow often becomes channeled in these gullies also, causing headward erosion, expansion of the drainage system and thus disturbance of adjacent upland sediments. Lakes and ponds may be captured by this process.

Vegetation and the associated peat layer are important in maintaining the thermal regime of perennially frozen sediments. A well-developed organic mat will slump over banks following erosion of underlying sediments and then act as a thermal blanket over the bank face.

A number of authors have suggested that permafrost accelerates erosion; others have concluded the opposite. Clearly the precise role of permafrost in streambank erosion remains poorly understood. High rates of bankline recession have been measured, but detailed studies in conjunction with the measurements have been lacking. Typical rates of bankline recession reported in the literature range from 1 to 15 m/yr, but exceptional rates of over 60 m/yr have been measured.

Lawson (1983a) thoroughly reviewed the erosional processes along perennially frozen streambanks. He concluded that systematic, quantitative studies of eroding and non-eroding permafrost streambanks are needed to analyze: 1) the subaerial and subaqueous processes of erosion, 2) the physical properties of frozen and thawed bank and bluff zone sediments and their relationship to erosion, 3) the thermal characteristics of bank, bluff and channel bed materials, 4) the relative importance of erosional processes at each location, and 5) the volumetric displacement and bankline or bluffline recession rates in relation to specific erosional processes.

*Coastal storm surges**

The vegetation, soil and landforms immediately adjacent to the coast are strongly influenced by storm surges. Waves and currents impinge on the bluffs and degrade the ice-rich sediments (Hartwell 1972, Short 1973, Barnes and Reimnitz 1974, Harper 1978, Hopkins and Hartz 1978, Owens et al. 1980). As along streambanks, thermoerosional niching and other erosional processes occur along coastal bluffs. A major difference, however, is associated with seawater impact on the vegetation. In the fall, when storms are common and the ocean is free of ice within 10 km of the coast, large storm-generated waves carry seawater up estuaries and over the low coastal areas. The water that reaches inland areas does not readily drain from the landscape as it would along a steeper coastline. The saltwater collects in low areas and kills the sedge vegetation. Drier areas dominated by *Dryas integrifolia* and prostrate willows are particularly susceptible to salt kill, which is the cause of the dead, dry vegetation along most of the arctic coastline. These areas are often colonized by more salt-tolerant taxa such as *Braya pilosa* and *Salix ovalifolia*. They are a natural analog for human-caused seawater spills associated with pipelines for oil-field waterflood projects (Simmons et al. 1983).

Storm surges also cause extensive areas of ice pile-up and gouging (Fig. 7) along the coast. The storms can push mounds of beach sand, gravel, boulders, peat and tundra material more than 150 m inland (e.g. Kovacs 1983). Peaty substrates are particularly slow to recover in the cold coastal climate, but eventually they become revegetated with salt-tolerant forbs and graminoids.

Frost scars†

Frost action produces a great variety of disturbances that alter the microtopography, ranging from needle-ice to ice-wedge polygons (Washburn 1980). Frost scars, also called frost boils, are small circular areas of highly frost-active soil that often lack much vegetation cover. The size and abundance of frost scars depend on soil type, moisture status, vegetation and thermal regime. The area covered by frost scars ranged from 100% on some

* Prepared by D.A. Walker.

† Prepared by A.W. Johnson.

Figure 7. Ice-gouge features along Camden Bay in the Arctic National Wildlife Refuge. (Photo by D.A. Walker, 22 Aug 1982.)

Figure 8. Large frost scar at Prudhoe Bay. This scar has a hummocky raised marginal ring typical of many frost scars on wetter terrain in the region. (Photo by D.A. Walker, Aug 1974.)

fell fields and nets to 0% in some areas of wet tundra (Holowaychuk and Smeck 1979, Gartner 1982). Individual frost scars usually vary from 1 to 2 m in diameter.

Frost scars (Fig. 8) are analogous to small-scale anthropogenic disturbances. In fact, frost scars are often a major part of anthropogenic disturbances since these features apparently become increasingly active or reactivated when the vegetation is removed or disturbed. The summer thaw in frost scars is commonly two or three times deeper than in adjacent unscarred tundra. The increased thaw is due to the absence of an insulating organic mat, the greater thermal conductivity, and the

lower albedo. Depending on the type and amount of ground ice in the active layer beneath the scar, the surface may seasonally subside or remain raised. Rarely does deep subsidence and thermokarsting develop beneath frost scars.

There have been studies of temporal changes on frost scars with varying amounts of plant cover (Hopkins and Sigafoos 1951), but few studies have followed changes or recovery of frost scar surfaces through time. Recently, however, a 20-year record of change on permanently marked frost scars at Ogoturuk Creek (Cape Thompson) in northwest Alaska has provided some new information on frost scar recovery (Johnson and Neiland 1983, Everett et al. 1985). There appears to have been little or no change in the size of individual frost scars between 1961 and 1980. *Eriophorum angustifolium* and *Carex aquatilis* are the major species that are established or lost from frost scars in wet meadows.

Frost scars may be favorable habitats for establishment of *Eriophorum vaginatum* seedlings if a thin mat of vegetation, mostly moss or hepatics, develops first (Gartner et al. 1986). These seedlings, which grow into tussocks, can presumably become established after a series of years of adequate moisture and sufficiently rapid seasonal freeze-up to prevent needle ice from forming. The tussocks, however, eventually die and are replaced by other tussocks in different locations, so there is little change in total cover of vegetation with time.

*Animal disturbance**

Animal-related disturbances include animal dens, digging sites of bears, bird mounds, lemming activity, carcasses, waterfowl molting areas, caribou trails and areas of heavy grazing and browsing. Animal dens and bird mounds are rich in dicots and grasses, due in part to nutrient enrichment from the animal feces (Wiggins and Thomas 1962, Gersper et al. 1980, Walker 1985). Burrowing and the destruction of burrow systems by grizzly bears (Fig. 9) are confined largely to dry, often naturally unstable sites including river bluffs, pingos and tundra slopes. South-facing slopes are often sites of concentrated activity of foxes and squirrels, whereas snow banks are favored by lemmings. Many well-drained areas, such as pingos, stable sand dune areas and sandy riparian sites, are completely reworked by animals. Ground squirrels and foxes are responsible for zoogenic soils on pingos (Everett 1980). Grizzly bear diggings and fox dens have a large effect on the vegetation and morphology of pingos. Large-scale disturbance of vegetation by caribou

* Prepared by D.A. Walker.

Figure 9. Disturbance caused by a grizzly bear excavating for ground squirrels. These features are common on drier terrain, particularly along river terraces and on pingos. This site is on Beny Pingo about 55 km south of Prudhoe Bay. (Photo by D.A. Walker, 11 Aug 1982.)

trampling has been described by Bee and Hall (1956); caribou trails are possible analogs for some types of vehicle trails. Wiggins and Thomas (1962) described several other animal-related disturbances, including the impact of molting waterfowl, the distruction of tundra by hunting jaegers and the impact of brown lemmings. Lemmings are one of the principal factors that control the distribution of nutrients in the Barrow ecosystem (Pitelka 1964, 1973, Schultz 1964, 1969). Batzli et al. (1980) described several other influences of brown lemmings, including changes to microtopography, vegetation and soil; they compared these to the effects of caribou at Prudhoe Bay. Although the comparison with anthropogenic impacts has not been fully evaluated, animal-caused impact may provide some of the best natural analogs for small-scale human disturbances.

*Fire**

Lightning-caused tundra fires in the Alaskan Arctic have been described from the Yukon-Tanana uplands (Wein and Bliss 1973a, Wein 1975), the Seward Peninsula (Racine 1981), the Noatak River area (Racine et al. 1985) and the Arctic Foothills-Kokolik River area (Hall et al. 1978, Johnson and Viereck 1983). Human-caused tundra fires have occurred rarely in the past but are likely to be more common as resource exploration and development proceeds.

The size and importance of tundra fires (based on 25 years of records) varies widely within the Arctic (Wein 1976, Gabriel and Tande 1983). Tundra fires are rare on the Arctic Coastal Plain, Arctic Foothills and Central and Eastern Brooks Range but are more common in northwest Alaska. The Seward Peninsula is the area of greatest fire occurrence (9.7 million acres over 23 years) followed by the Noatak River-Western Brooks Range region. Fire records in these areas are the basis for establishing a gradient of fire rotation time, that is, the length of time necessary for an area equal to the entire area of interest to burn. Preliminary estimates of fire rotation times are 200–250 years in the Seward Peninsula-Noatak River-Kotzebue Sound area, 10,000+ years in the Arctic Foothills, and over 3000 years in the Central and Eastern Brooks Range. This compares with rotation times of 150-300 years in the tiaga of interior Alaska (Gabriel and Tande 1983, Racine et al. 1985). Fires are very rare on the Arctic Coastal Plain, and estimates of fire rotation times there are inappropriate. This gradient of fire rotation times follows a gradient of summer drying regimes and lightning storm occurrence.

Fire severity varies with the terrain-substrate-vegetation type (geobotanical unit), the timing (early or late in the growing season) and the weather conditions during the fire (wind, temperature, humidity). A tundra fire can superficially remove or scorch the above-ground plant stems and leaves, or it can totally consume all plant and organic material down to mineral soil.

Tussock-sedge, mixed-shrub tundra is the most frequently burned tundra vegetation type because it is common, it is very susceptible to drying, and it is inherently flammable. Severe fires can also occur in nontussock, better-drained, shrub-dominated habitats. Fires seldom occur on drier alpine tundras at higher elevations or river gravel bars because fuel accumulates very slowly in these areas. Riparian shrub thickets seldom burn, but areas with scattered tall shrubs or small drainageways with low willow shrubs can sustain severe, intense fires.

In the Seward Peninsula, plant cover increases rapidly following light and moderate fires in tussock-sedge, mixed-shrub tundra. Plant regrowth produces 10–30% cover of vascular vegetation by the end of the first summer following a fire, 50% by the fifth year, and 100% cover by the tenth year (Racine et al. 1983). The recovery is rapid because the leaves of fire-resistant cottongrass (*Eriophorum vaginatum*) tussocks regrow quickly. Low shrubs resprout more slowly than sedges and contribute less to early recovery. Grasses (e.g. *Poa* spp., *Calamagrostis* spp., *Arctagrostis latifolia*) are locally important following fires in tussock tundra. When severely burned, both cottongrass tussocks and shrubs may be killed, and recovery of the vegetation is slower. For example, vascular plants covered only 33% of a tussock-sedge, mixed-shrub tundra area in the arctic foothills five years after a severe burn (Johnson and Viereck 1983).

On dry slopes covered with dwarf shrubs, burning is often severe enough to remove both the vegetation and the shallow soil organic layer. Mosses and liverworts colonize rapidly; by the second year, bryophyte cover is 50% and may locally reach 100%. This cryptogam revegetation may persist for a number of years. In the Kokolik burn (Hall et al.1978), severely burned peaty high-centered polygons were predominantly covered by bryophytes after five years (Johnson and Viereck 1983).

* Prepared by C. Racine

Seeding by vascular plants is an important revegetation mechanism in other areas. In the Seward Peninsula, sedges (*Carex* spp.) established from seed covered 50–100% of better-drained sites within six years after a fire (Racine et al. 1983). On other well-drained, willow-dominated sites on the Noatak River and Seward Peninsula, dense stands of fireweed (*Epilobium angustifolium*) developed within two years following a fire and have persisted for at least 10 years.

Severely burned dwarf-shrub communities may not recover completely for 50 years or more, but vascular and nonvascular plants establish rapidly and reach 100% cover within as few as six years following a fire if sufficient moisture is available. Some sites remain vegetated only by a thin moss layer for more than 10 years and show little sign of change or invasion by vascular plants. Other sites remain vegetated by grass or fireweed for 10 years or more.

Increased thawing, subsidence and erosion in tussock-sedge, mixed-shrub tundra is usually minimal since this tundra type generally occupies gentle slopes. Thaw stabilizes within 10 years; however, Johnson and Viereck (1983) described two areas on the Kokolik River burn where massive ice was exposed as a result of erosion and thermokarsting related to the fire. It is not known when the active layer depth, surface subsidence or hydraulic erosion will stabilize at severely burned sites.

Anthropogenic disturbances

Three distinct periods of anthropogenic disturbances have occurred on Alaska's North Slope: 1) the pre DEW-line period, which was mainly limited to activities associated with native villages, 2) the DEW-line and early exploration period, including the exploration of Naval Petroleum Reserve-A from 1943 to 1953 (Schindler 1983, Gryc 1985), which pre-dates the era of national environmental consciousness, and 3) the period starting with the National Environmental Policy Act (1970) to the present. The disturbances discussed in this section are mainly related to oil exploration. Many disturbances are still visible from the earliest oil exploration, when tracked vehicles fanned out across the tundra from Barrow and drilling was done with little concern for environmental consequences (Hok 1969). By the late 1960s, environmental controls of off-road vehicles and construction activities were being established in response to accelerating environmental awareness. Since then, environmental protection regulations have reduced initial impacts. During the late 1970s, many innovative techniques for temporary construction and transportation were applied along the trans-Alaska pipeline route, in the NPR-A, and in the Arctic National Wildlife Refuge (Brown and Hemming 1980, U.S. Fish and Wildlife Service 1982, Brewer 1983, Morehouse 1984). The major concerns now are shifting from direct physical impacts to cumulative effects, which are more subtle

Table 2. Classification of disturbance by activities and their initial modification to vegetation, soils and sediment. (From Lawson 1982.)

Type of disturbance	*Initial modification*	*Types of activities*
1	Trampling and compaction of vegetation	a. Off-road vehicle movements, single and multiple passes by wheeled and ski-mounted vehicles.
		b. Snowpads (e.g. winter trails).
		c. Footpaths.
		d. Temporary storage of supplies.
2	Killing of original vegetation	a. Hydrocarbon spills (diesel fuel, crankcase oil)
		b. Boardwalk and elevated buildings.
		c. Solid waste (e.g. steel drums, tarps, woodpiles, nondegradable waste).
		d. Berms (spoil piles) formed along bulldozed trails and excavations.
3	Removal of vegetative mat	a. Shallow bulldozed roads.
		b. Shallow excavations for building foundations.
		c. Piling (local).
		d. Tracked vehicle movements.
4	Removal of near-surface sediment with vegetative mat	a. Bulldozed roads.
		b. Excavation of trenches, drainage ditches and sump.
		c. Basement excavations for drill rig piling.

and difficult to study. In this discussion, anthropogenic disturbances are divided into three categories: 1) off-road transportation, 2) permanent or semipermanent facilities, including roads, pads and material sites, and 3) contaminants, such as oil and saltwater spills. Lawson (1982) used four categories to classify disturbances based on the initial modification of the vegetation, soils and sediments (Table 2). This grouping is similar to one proposed by How (1974) and Grave (Brown and Grave 1979).

Off-road transportation

The boggy summer landscape of northern Alaska presented a formidable transportation challenge to the oil exploration efforts of the 1940s to 1960s. Experimentation with different modes of transportation was essential because of the lack of familiarity with permafrost (Reed 1958). Most of the early vehicles and road construction methods were borrowed from temperate regions and adapted to the cold climate. The first transportation corridors were trails that were bladed to the permafrost table by bulldozers; these eventually formed deeply rutted trails as ground ice melted and water ponded in the depressions. In some areas peat roads using adjacent tundra were constructed. Although recent oil exploration and development was accompanied by a trend toward more permanent transportation corridors, all-season off-road transportation is still needed. Vehicle designs have become increasingly sophisticated to minimize the damage to tundra landscapes. This section reviews the results of studies of bulldozed trails, summer off-road vehicle trails, and winter snow and ice roads.

*Bulldozed trails.** During the early years of oil exploration in NPR-A (1944–1953) and the exploration of the central coastal plain and foothills during the late 1950s, trails were commonly bulldozed across the tundra during both summer and winter (Reed 1958) (Fig. 10, 11). In places these trails extended long distances across the Arctic Coastal Plain (e.g. the Oumalik trail from Barrow to Umiat and the Hickel Highway from the Yukon River to the North Slope). Bulldozing was also carried out locally for excavations, foundations, drill pads, aircraft runways, sewage disposal, and snow clearing (Lawson et al. 1978, Lawson 1982). Caterpillar tractors were used most frequently to create trails. Bulldozers were also used in building

* Prepared by K.R. Everett, J.J. Ebersole, V. Komárková and D.E. Lawson.

Figure 10. Bulldozed trail to Prudhoe Bay constructed in the 1960s. The trail now parallels the Dalton Highway (right background). This site is on the Sagwon Upland approximately 110 km south of Prudhoe Bay. (Photo by D.A. Walker, 21 Aug 1983.)

Figure 11. Erosion channel along the trail to Prudhoe Bay. Massive ice in the uplands has resulted in over 3 m of erosion. The resulting gully is a protected microsite that permits willow growth up to 2 m tall. Willow growth is enhanced by the warmer soils, deeper thaw, high decomposition rates and richer nutrient regimes. (Photo by D.A. Walker, 21 Aug 1983.)

Figure 12. Peat road near Prudhoe Bay. (Photo by D.A. Walker, 27 July 1984.)

Figure 13. Surface of a peat road near the Putuligayuk River in the Prudhoe Bay oil field. The ponded water in the scraped areas creates wide barriers on both sides of the road. The water has also eroded the road bed, making it impassable. These surfaces are very slow to revegetate; this road is at least 15 years old. Most of the plant cover is mosses (e.g Bryum *spp. and* Ceratodon purpureus*). The vascular taxa include* Carex aquatilis, Braya pilosa, Deschampsia caespitosa, Puccinellia andersonii, Draba alpina, Saxifraga hirculis *and* S. oppositifolia. *(Photo by D.A. Walker, 31 July 1983.)*

peat roads (Fig. 12, 13). These roads were made by removing peat from both sides of the road and piling the material in the center to form a raised surface. The scraped margins of the roads quickly subsided due to the thermal erosion, particularly along ice wedges. Bulldozing the tundra for roads is prohibited today.

The severity of bulldozer damage ranges from compression of microtopographic irregularities to removal of the entire vegetation mat and near-surface sediments. Bulldozing is included in types 3 and 4 of Lawson's (1982) classification, which represent severe disturbances (Table 2). Of all the means of off-road travel, bulldozed trails represent the most severe and long-lasting disturbance to tundra vegetation, soils and permafrost. Not only does bulldozing often remove vegetation and soil from the center of the trail, but it also involves piling the material in berms or mounds on the edge of the trail, burying the vegetation and creating a habitat quite different from the adjacent tundra.

Bulldozing ice-rich areas inevitably causes the permafrost to melt, the ground surface to subside, and the depressions to fill with water. The amount of subsidence is a function of the ice volume and parent material. At Fish Creek and Cape Simpson (Fig. 14), where there are relatively small amounts of massive ground ice and sandy materials, the amount of subsidence after 30 years is 0.4–2 m; at East Oumalik (Fig. 15 and 16), where there are large amounts of ground ice and mainly silty sediments, the amount of subsidence after 30 years is 3-5 m (Lawson 1982). Hydraulic erosion commonly accompanies subsidence on slopes. At Fish Creek, degradational processes probably diminished within five to ten years after bulldozing ceased. At East Oumalik, however, thermokarst is still expanding laterally in some areas because of hydraulic and thermal erosion and continued thawing of sediments. Now, after 30 years, the disturbance covers at least twice the area of the initial disturbance (Lawson 1982). This has also occurred along many bladed trails throughout the foothills (Fig. 10 and 11).

Recovery on bulldozed sites depends largely on the site moisture regime. Trails in wet meadows

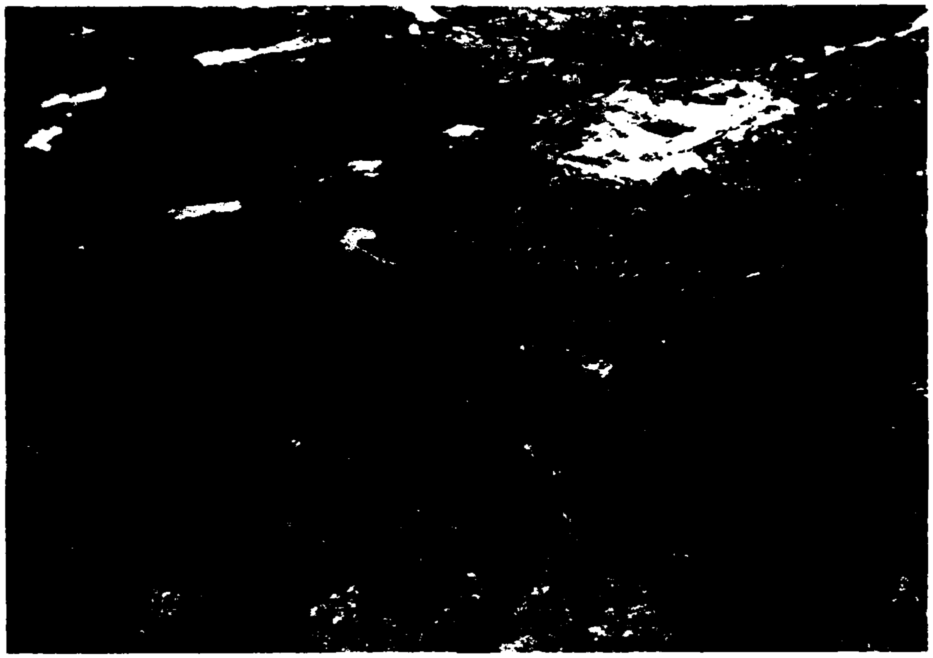


Figure 14. Simpson Test Well after clean-up. This site is within 2 km of the arctic coast. The cold, windy, coastal climate is responsible for the barren polygon tops that persist 30 years after the initial disturbance. (Photo by J.J. Ebersole, 23 July 1980.)

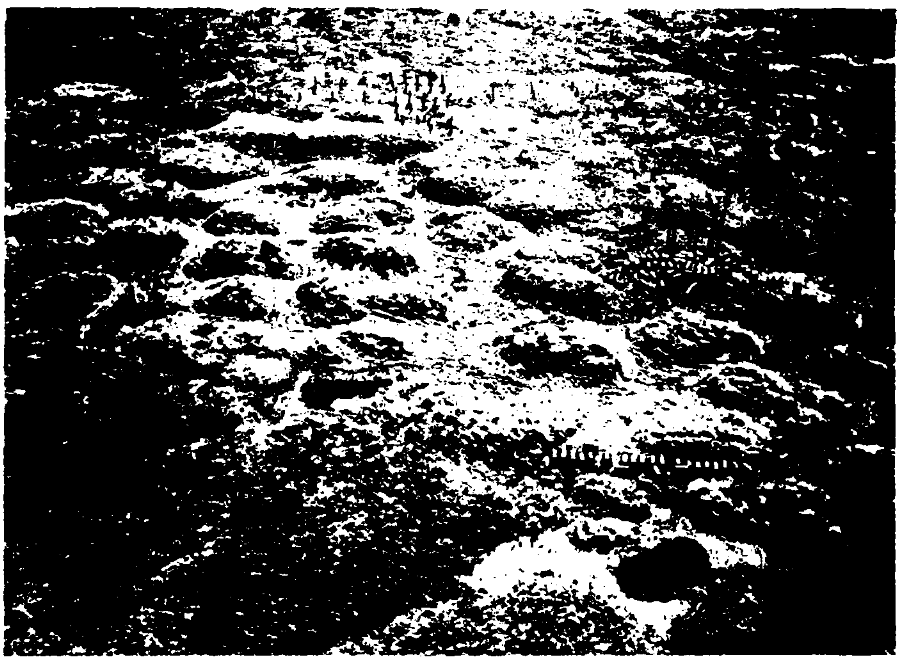


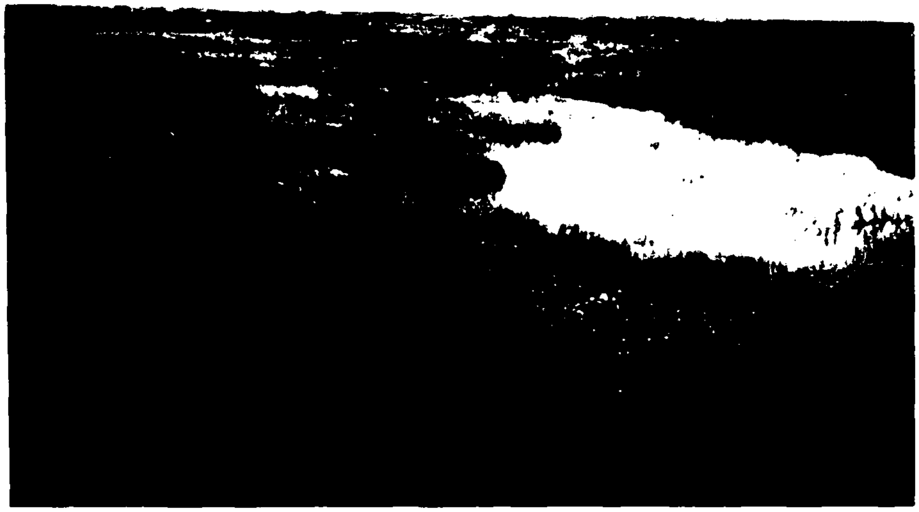
Figure 15. Oumalik Test Well site. This well was drilled in 1949-1950 and was not disturbed until it was cleaned up in 1980. The site was level moist tundra before it was disturbed. Extensive thermokarst has resulted in a field of high-centered polygons. Compare the thermokarst at this site with that at the Simpson Test Well (Fig. 14), which is in an area of less ground ice. (Photo by J.J. Ebersole, 30 Jun. 1979.)

Figure 16. Local relief developed due to thermal erosion at the East Oumalik Test Well. This site is about 18 km southeast of the Oumalik site in Figure 15. Relief up to 5.5 m developed at this site because of large quantities of ground ice, well-developed local relief, and silty soils (Lawson 1982). (Photo by J.J. Ebersole, 11 July 1981.)

underlain by sediments with low ground-ice volumes generally contain few thermokarst pits and are not normally affected by hydraulic erosion because of the relatively level terrain (Johnson et al. 1978, Ebersole and Webber 1983, Ebersole 1985). Thirty years after wet meadows were bulldozed at Fish Creek, Oumalik and many other old drill sites across NPR-A, subsidence has generally stopped and there is a complete cover of vascular plants (Komárková 1983b, Ebersole and Webber 1983). *Carex aquatilis* and *Eriophorum angustifolium* provide essentially all the cover except near the arctic coast, where *Dupontia fisheri* is also important. These species dominate bulldozed areas where water is less than about 25 cm deep or where there is no standing water but the soils are still very wet by the end of the summer. Only a few other vascular plants have invaded, and they provide little cover. These communities are similar to undisturbed, low-diversity marshes that occur in the early successional phases of wet drained-lake basins (Peterson and Billings 1980). Where the water is deeper than about 40 cm but less than 1 m, *Arctophila fulva* and sometimes *Hippuris vulgaris* are present, forming a simple community much like the natural ones in shallow ponds and lake margins. If water is deeper than 1 m, there is generally no vegetation.

In moist tussock-sedge, mixed-shrub tundra, bulldozing often removes the tussocks and the underlying organic mat, which causes water to accumulate and converts the vegetation to wet sedge tundra composed of *Carex aquatilis* and *Eriophorum angustifolium* (Johnson et al. 1978). There is little tendency toward a return to the original community. However, in less severely disturbed areas where the bases of the tussocks and intertussock plants are intact, the tussocks regrow slowly. Seedlings establish slowly where the moist vegetation has been scraped away, leaving a thick organic mat. Seedling establishment is especially slow near the coast (Racine 1977, Johnson et al. 1978, Ebersole and Webber 1983). Willow seedlings are common and willows are an important component of the vegetation cover on 30-year-old bulldozed areas at Oumalik (Ebersole 1985) (compare Fig. 17 with Fig. 18 and 19).

In dry sites, bulldozing generally results in a barren mineral surface that becomes revegetated through a process of primary succession. The type and level of recovery depends mainly on the amount of fine materials remaining after bulldozing (Everett et al. 1985). Disturbed, well-drained rocky soils in the foothills (for example, at Cape Thompson, Knifeblade Ridge and Wolf Creek) do not attain their full potentiai cover in 30 years (Everett et al. 1985, Ebersole 1985). Willows grow vigorously on most of these areas, but the understory cover is moderate to sparse. At the Simpson Test Well, a cold coastal site east of Barrow, many organic-rich high-centered polygons have been disturbed by vehicles; the vegetation was killed but



ure 17. Disturbed polygons with organic-rich soils at the Simpson Test Well. Compare the vegetation recovery at this cold coastal site with that of the relatively warm inland sites at Oumalik and East Oumalik (Fig. 15, 16 and 18). Primary vascular taxa on the moist disturbed sites are Luzula confusa, Arctagrostis latifolia, Salix pulchra, Stellaria *sp. and* Poa arctica. *Nearby undisturbed sites are dominated by ericaceous shrubs. Bladed areas at this site were dominated by* Arctagrostis latifolia *and* Dupontia fisheri. *Willows are not an important component of the vegetation on disturbed sites. (Photo by J.J. Ebersole, 21 July 1980.)*

not removed, leaving a thick organic mat in which seedling establishment is difficult (Johnson et al. 1978) (Fig. 14 and 17). These sites are also blown free of snow in winter, making seedling establishment even more difficult. Dry, highly organic soils on high-centered polygons near the coast at Barrow and other coastal sites are often naturally unvegetated due to the winds and dry seedbeds.

Bulldozed trails commonly have banks or berms composed of material pushed from the center of the track. If an intact piece of turf is flipped upside down, exposing a thick organic mat, colonization is slow, presumably because seedling establishment is difficult on the dry, peaty material. A similar environment occurs on peat roads (Fig. 13). Observations from Oumalik (Ebersole and Webber 1983) show that where the material forming the berms is mixed with mineral soil, plant cover is high and composed mainly of *Arctagrostis latifolia*, *Poa arctica*, *Betula nana* and *Festuca brachyphylla*. Mounds of bulldozed material up to 1.5 m high are well-drained microsites with higher soil temperatures and thick active layers. Decomposition rates and nutrient availability are consequently higher than in the adjacent tundra (Lawson et al. 1978). For example, at Oumalik, temperatures at a depth of 10 cm on 30 June 1980 averaged 9.4°C in bulldozed material, compared with 2.4°C in adjacent tussock-sedge, dwarf-shrub tundra and 5.6°C in wet sedge tundra (Ebersole and Webber 1983). After 20-30 years, grasses and erect willows, particularly *Arctagrostis latifolia, Salix alaxensis, S. glauca, S. lanata* and *S. pulchra*, form a complete cover and grow more vigorously than in the surrounding undisturbed tundra (Ebersole 1985) (Fig. 18 and 19).

*Off-road vehicles—summer travel.** Off-road vehicles have been used for a wide range of summer activities, including seismic operations, drill-site activity, mining, scientific research, reindeer herding, subsistence activities and recreation. Vehicles vary in type and size and include tracked "weasels" and bulldozers, four-wheel-drive trucks,

* Prepared by G. Abele, K.R. Everett and D.A. Walker.

Figure 18. Lush willows at Oumalik 30 years after it was disturbed. This vegetation formed on mounds of bulldozed material in what was formerly a drained lake basin similar to that in the background. The general height of the willows is at the winter snow level. The primary species are Salix lanata, S. pulchra, S. glauca *and* S. alaxensis. *Occasional taller willows such as that in the center are invariably* S. alaxensis, *which can survive the bitter winter conditions above the general snow level. (Photo by J.J. Ebersole, 3 July 1979.)*

Figure 19. Vegetation on displaced bulldozed material at Oumalik. This photo was taken prior to the clean-up operations in 1980. (Photo by J.J. Ebersole, 21 July 1979.)

and vehicles with low-pressured tires, such as "Rolligons" and light-weight three-wheeled all-terrain cycles. Air-cushioned vehicles showed much promise for low-impact transportation on flat tundra (Abele et al. 1972), but they have not been widely used on land due because of their high operating costs and their inability to traverse hilly areas.

Vehicle impacts and recovery were monitored for up to 10 years following tests at Barrow, Lonely and Prudhoe Bay (Abele et al. 1972, 1978, 1984, Walker et al. 1977). At Cape Thompson, vehicle trails used for research between 1959 and 1961 and then abandoned were examined in 1981 (Everett et al. 1985). In addition a variety of 25- to 30-year-old off-road vehicle trails were studied at Fish Creek (Lawson et al. 1978), East Oumalik (Lawson 1982) and Oumalik (Ebersole 1985). Hok (1969) also documented trails of similar age.

Cross-tundra vehicle traffic may produce all levels of initial disturbance, ranging from simple compression of the vegetation to displacement and removal of the vegetation (Walker et al. 1977, Abele et al. 1978, Everett et al. 1978). The actual effect is determined by many factors, including type of vehicle, acceleration, turning radius, speed, time of summer, number of passes on the same trail, slope, type of terrain and vegetation. Even one pass of a vehicle can leave a conspicuous track that lasts more than 30 years (Lawson 1982). At Prudhoe Bay (Walker et al. 1977) and Lonely (Abele et al. 1978), single-pass Rolligon tracks through wet tundra were initially very visible, but in seven years the tracks could not be traced on the ground. However, documented single-pass trails of overloaded Rolligons in wet tundra are still apparent after 10 years.

The resistance and resilience of tundra to vehicle disturbance varies according to vegetation type. For example, moist sedge, dwarf-shrub tundra is more resistant to single-pass Rolligon tracks than wet sedge tundra, but it is less resilient. In moist tundra at Prudhoe Bay the initial tracks were not particularly damaging to moist tundra, but there was some compression of hummocks and ice-wedge polygon rims. This small amount of impact tended to persist for five years (Walker et al. 1985c). In 10-pass Rolligon tracks at Prudhoe Bay, the initial disturbance was particularly severe in wet tundra, where there was considerable displacement of material to either side of the tire tracks. After seven years, the track is still depressed by 15-20 cm in wet tundra, and the tracks are conspicuously greener than the surrounding area. The surface collapsed up to 30 cm and flooded with water wherever the tracks crossed ice wedges. Fresh collapse features in the troughs indicate that thermal equilibrium has not been reestablished within seven years (Walker et al. 1985c).

After 20–30 years, deeply rutted tracks in wet tundra at Cape Thompson (Everett et al. 1983), Oumalik (Ebersole 1985), Fish Creek (Lawson et al. 1978) and Barrow (Abele et al. 1972) apparently have reached thermal equilibrium and support typical wet-tundra plant species. In many areas this wet tundra is very different in composition from the initial vegetation (Fig. 20). *Carex āquatilis, Eriophorum angustifolium* and other sedges have invaded these tracks from the adjacent undisturbed area by means of rhizomes, but forbs and shrubs are generally less important in the tracks than in the undisturbed areas. The growth of the sedges is greater in the tracks than in the surrounding tundra, and the tracks are often noticeably greener than the undisturbed tundra. This "green belt" effect is possibly due to increased oxygen and nutrient movement resulting from runoff that is seasonally channeled in the tracks (Challinor and Gersper 1975, Gersper and Challinor 1975, Chapin and Shaver 1981, Linkins and Stewart 1984).

The depth of summer thaw often increases after impact but tends to rebound in later years. At Barrow the initial depression of a wet meadow surface was 15 cm in a 50-pass weasel track test. Seasonal thaw increased an average of 10 cm after two years but returned to predisturbance levels within 10 years (Abele 1976). In wet meadows at Cape Thompson no significant differences in thaw depths were found in severely disturbed trails and adjacent controls after 20 years (Everett et al. 1985). The depressed surface in tracks in wet sedge tundra at Barrow (Abele 1976) and Cape Thompson (Everett et al. 1985) have rebounded, presumably due to subsurface ice aggradation. Nearly complete vegetation recovery from the vehicle traffic is likely within five years on flat tundra if the vegetation mat is not broken. However, if the mat is broken or if runoff water is channeled in the track, recovery is likely to be slow. For example, a wet meadow solifluction slope at Cape Thompson showed little vegetation recovery after 20 years as a result of hydraulic erosion and channeling up to 2 m deep (Everett et al. 1985). Where off-road vehicle tracks break and churn the organic mat over ice wedges, subsidence and thermokarst formation result from thaw and melting of the massive ice (Abele 1976, Lawson et al. 1978, Lawson 1982). At Prudhoe Bay the thermokarst ponds are still slowly increasing in size seven years after the impact (Walker et al. 1985c); at East Ou-

Figure 20. Thirty-year-old vehicle tracks in a drained lake basin at Oumalik. This trail was created by many passes with a weasel tracked vehicle. The soils of the former low-shrub, sedge tundra were compressed, which eliminated the drier microsites where willows could grow and created a wet microenvironment where only sedges and mosses could grow. (Photo by J.J. Ebersole, 24 July 1980.)

malik, Oumalik and Fish Creek the impact sites appear to have physically stabilized after 30 years, and vegetation covers most areas.

Off-road vehicle disturbances in dry, rocky fell fields often revegetate extremely slowly. Little or no invasion by vascular plants, lichens or mosses has occurred after 20 years at Cape Thompson on an alkaline fell field (Everett et al. 1984). A nearby acidic fell field, however, shows some recovery with mosses and numerous forbs. Dry, exposed fell fields and sandy ridges with little or no soil, low soil moisture, and high wind exposure show slow recovery once the vegetation is removed.

Abele et al. (1984) presented results of 10 years of observations involving six vehicle types (three low-tire-pressure Rolligon vehicles, two light-weight tracked vehicles, and one air-cushioned vehicle) at Barrow and Lonely, Alaska, on coastal wet sedge tundra and on moist sedge, dwarf-shrub tundra. In general, the air-cushioned vehicle produced the least impact. All three Rolligons produced longer-lasting impact than the light-weight tracked vehicles. This was mainly a function of higher ground pressure for the Rolligons than for the tracked vehicles (0.07-0.1 kg/cm^2 for the tracked vehicles vs 0.25-0.35 kg/cm^2 for the Rolligons). Rebound of the depressed tundra surface has occurred with all vehicles and amounted to up to 15 cm in the case of 50 passes with a weasel.

Abele et al. (1984) concluded that the tundra vegetation will usually recover to nearly its original state within 10 years if the disturbance from vehicular traffic only causes a depression of the surface. This holds for even seemingly serious damage to wet tundra vegetation, as long as there is no damage to the root systems. If the organic mat is sheared or separated, the result, at least in wet and moist coastal tundra, is a water-filled depression that is unlike the original tundra and very slow to recover completely.

*Winter trails and snow and ice roads.** In winter a road may be prepared by smoothing or compacting the snow surface to form a snow road or by spraying water on the surface to build up an ice layer to form an ice road (Gas Arctic-Northwest Project Study Group 1973, Adam 1974, Adam and Hernandez 1977, Johnson and Collins 1980). Snow and ice roads have been used in a variety of situations in northern Alaska. For example, Recent explorations of NPR-A took place during the winter over unprepared snow trails and prepared

* Prepared by K.R. Everett and D.A. Walker.

snow roads and ice roads. In another situation, a snow pad was built adjacent to the TAPS haul road during the construction of a 230-km gas line during the winters of 1975–76 and 1976–77 (Brown and Berg 1980, Johnson 1981). The Hickel Highway to the North Slope was intended as a snow road during the winter and was used for several winters in the 1960s, although the majority of it ended up being bulldozed. Aircraft landing strips have also been prepared using packed snow or ice.

Disturbances and recovery resulting from winter trails and snow and ice roads have been studied at Prudhoe Bay (Buttrick 1973), at Inigok in NPR-A (Everett, unpub. data) and in the Seward Peninsula (Racine 1977). The impact to both vegetation and animal populations in winter is considerably less than the effect of off-road activities in the summer. Winter off-road vehicle travel can, however, cause severe disturbances where snow plowing is necessary or where frozen tussocks are easily knocked over due to insufficient snow or ice cover (Racine 1977). Most of the effects of ice roads are related to direct physical disturbance to the vegetation, debris from the road, and destruction of the highly porous subnivean layer.

In the spring of 1972 an experiment was conducted at the Prudhoe Bay Arctic Gas test site to evaluate the impacts of single-pass and multipass traffic over low-centered polygons on an unprepared snow surface (Buttrick 1973). The vehicle was a D-9 Caterpillar (8 kg/cm^2 bearing pressure). Two passes completely destroyed the subnivian layer (depth hoar), and with repeated passes, the snow was compressed and recrystallized. The standing dead vegetation of the wet sedge tundra in the polygon centers was completely flattened, and vascular plants and cryptogams on the polygon rims were crushed and broken. The test was halted before the track actually contacted the surface. After the spring thaw, no changes in thaw depth were recorded in either the single-pass or multipass test. The biomass of the standing dead vegetation was the same in both tests, so all damage to this component of the vegetation must have been done with one pass. The biomass of the standing green component was up to 79% less than in the control, with the vegetation on polygon rims (0.2–0.3 m high) accounting for most of the difference. The single pass did not significantly reduce flowering, as was the case in the multipass test. Productivity was reduced about 55% in the multipass lane. Again, the rim areas were the most severely damaged.

A heavily used ice road was built in the spring of 1978 between the Kikiakrorak River and the NPR-A drill site at Inigok, a distance of about 40 km. When viewed from the air in the summer of 1978, the impact of the road appeared slight. In part, this was because the road traversed mostly tussock-sedge, dwarf-shrub tundra, where the compression of standing dead vegetation is less obvious than in wet sedge tundra. However, ground observations revealed a variety of vegetation disturbances ranging from abraded and crushed tussocks to willows with broken or abraded terminal stems. By 1981 most *Eriophorum vaginatum* tussocks affected in 1978 were recovering. However, some plants were still compressed, and there were areas of numerous dead tussocks, mostly those that had been severely crushed or broken; there were also a few dead willows. Especially apparent was the alteration or destruction of the intertussock plant community, particularly the mosses (*Sphagnum* and *Dicranum*) and lichens. These species are apparently very susceptible to compression when frozen. The full impact on these species apparently does not become expressed until the second summer following the impact. The active layer was slightly thicker under the ice road area than in the adjacent tundra. Observations in Canada suggest that the seasonal thaw will return to pre-impact thicknesses within a few years (Everett, unpub. data).

Where snowpads are used for construction, considerable debris is deposited on their surfaces. The snowpads used for excavating the TAPS fuel gas pipeline and for constructing a section of TAPS (Johnson and Collins 1980) affected both the soil thermal regime and the vegetation. Up to 90% of the pad along the fuel gas line was covered with debris, while 25% of the TAPS snowpad was covered. The thaw depths under the pads increased for at least three years, reaching maximums of 22.3 cm deeper than controls along TAPS and 28.3 cm deeper along the gas line. The total vascular plant cover was reduced under the area of the snowpad during the first growing season after use, with erect shrubs (*Salix* spp. and *Betula nana*) showing extensive breakage. Under the TAPS snowpad many *Eriophorum vaginatum* tussocks were compressed or sheared off. However, vascular plants recovered after three years, but the amounts of mosses and lichens were still reduced compared to control areas (Johnson 1981).

*Seismic trails**

All seismic activities on the North Slope are now conducted in winter, and most of the recent studies involving vehicle impact have been related to the effects of winter seismic operations (e.g. Reynolds 1981, Felix and Jorgenson 1984, Geophysical Services, Inc. 1985). An area where winter vehicle trails are of particular concern is the coastal plain of the Arctic National Wildlife Refuge (ANWR), which was opened to winter seismic surveys in the winters of 1984-85 and 1985-86. The overall impact was generally minor, but some areas received considerable surface damage (Felix and Jorgensen 1984) (Fig. 21-23).

Observations of seismic trails left from the winter operations in ANWR show that dry tundra (Fig. 22) was the most noticeably affected of four common broad vegetation categories (dry tundra, moist nontussock tundra, moist tussock tundra, and wet tundra) (Walker, unpub. data, Felix and Jorgenson 1984). In places where there was little winter snow cover, up to 85% of the vegetation cover had been destroyed in swaths 10 m wide and up to 50 m long. The primary taxa affected in dry sites were *Dryas integrifolia, Oxytropis borealis, O. viscida* and *O. nigrescens*. The moss cover was reduced from 40% in unaffected areas to 15% in affected areas. The plant cover that remained in the denuded dry sites was confined primarily to low microsites such as interhummock areas; most hummocks were flattened and denuded. The edges of river terraces were also broken off and denuded.

The moist tundra was the least affected of the four types studied, but peaty hummocks and bird mounds (hillocks up to 1 m high believed to be the result of higher vegetation productivity caused by perching birds [Walker et al. 1980]) were flattened. Erect dead sedges were also flattened and absent within the track, causing a noticeable green swath (Fig. 23). The species composition of affected wet and moist sites was not noticeably different from the unaffected sites, except on the few elevated hummocks where scraping occurred. In these areas the surface albedo was higher because of the loss of the erect dead sedge component, and the microenvironment was wetter within the track because of surface depression.

In areas of tussock-sedge, mixed-shrub tundra, the traffic scuffed many cottongrass tussocks and killed many of the higher moss hummocks. Areas where the tracks crossed local snow accumulations, such as at the base of low terraces, showed none of the damage that was noted in less protected sites. The quantity and type of snow sufficient to protect the various tundra vegetation types from seismic operations in winter are still unknown. The major impacts from the 1984 and 1985 seismic operations were mainly aesthetic since there is not likely to be much long-lasting

* Prepared by D.A. Walker.

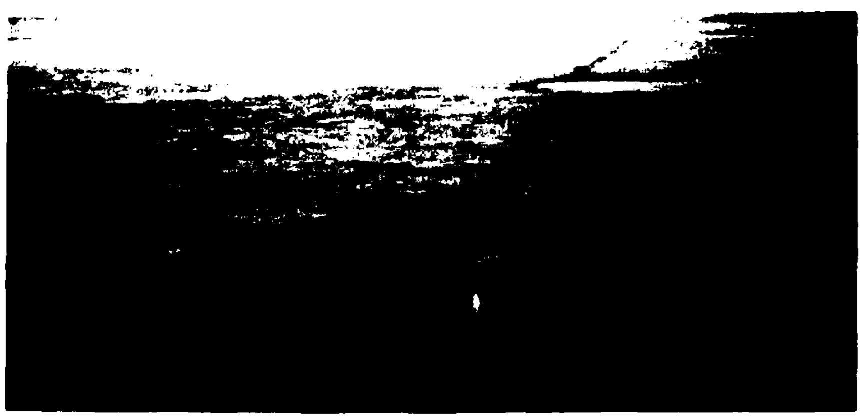


Figure 21. Winter seismic trail created in 1984 near the Hulahula River in the Arctic National Wildlife Refuge. (Photo by D.A. Walker, 18 Aug 1984.)

Figure 22. Damage from winter seismic operations on a dry river terrace of the Hulahula River. Considerable mineral soil has been churned, and most vegetation, principally Dryas integrifolia, *was killed within the track. (Photo by D.A. Walker, 18 Aug 1984.)*

Figure 23. Damage from winter seismic operations in wet sedge tundra. Most of the microrelief associated with moss hummocks, ice-wedge polygon rims and bird mounds has been eliminated. The width of the track at this site is approximately 15 m. (Photo by D.A. Walker, 18 Aug 1984.)

damage to the substrates or terrain features, but how long the tracks will remain visible from the air is unknown.

Aesthetics is a major consideration in highly protected areas such as national parks, refuges and wilderness areas. The visible impact of the traffic signature is the most prominent, long-lasting and difficult-to-measure consequence of current seismic operations. One approach to measuring visual impact is that of Abele (Abele and Brown 1977, Abele et al. 1978), who evaluated damage by Rolligons using photographs of the

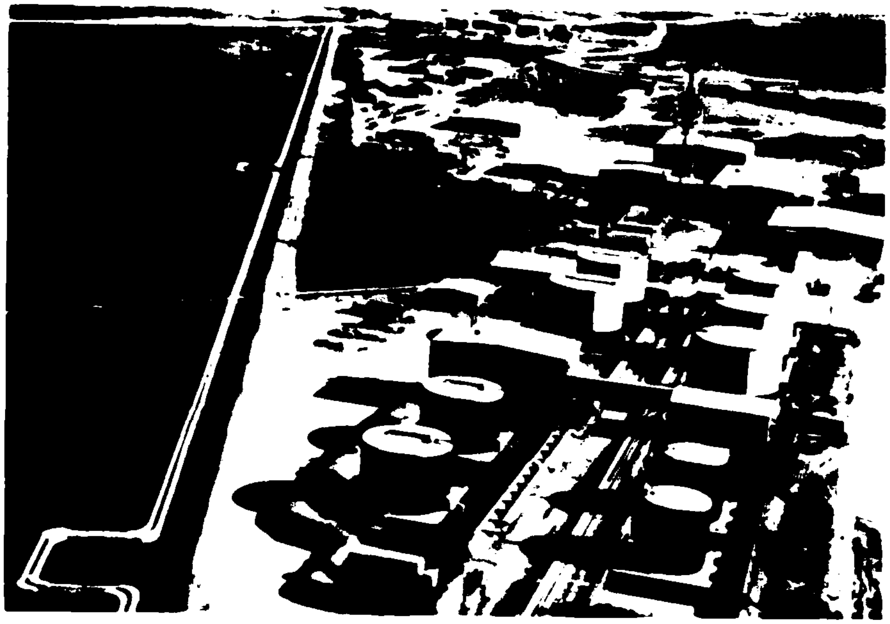


Figure 24. Part of the Prudhoe Bay oil field showing pipelines, roads and gravel pads. (Photo by D.A. Walker, 14 July 1981.)

track and a "visibility index." The index is a geometric progression (1, 2, 4, 8...); a doubling of the previous index value indicates a doubling of the apparent darkness of the vehicle signature on the photo. The darkness is measured with a tonal variation chart. More research is needed regarding methods of quantitatively describing visual impacts.

Permanent structures

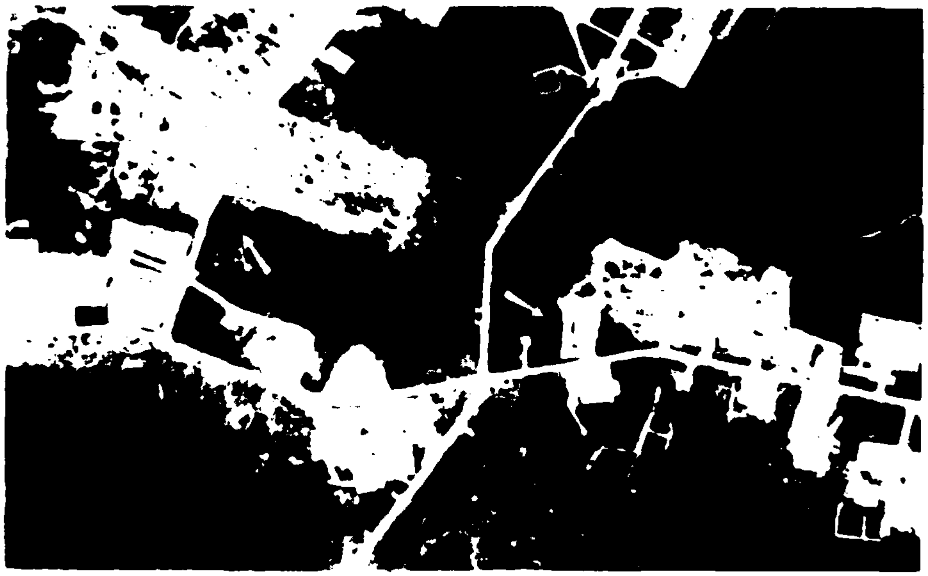
*Gravel pads.** Both exploration and development of arctic oil and gas deposits require construction of thaw-stable surfaces that must be able to support traffic and large structures such as drill rigs and heavy buildings. The Prudhoe Bay oil field was the first large oil development in northern Alaska. Within the Prudhoe Bay field, which does not include the nearby but equally extensive Kuparuk field, there are currently 40 drilling pads, 3 runways and 46 other large pads containing miscellaneous oil-field facilities, camps and storage areas (Fig. 24). These pads vary in size from less than 1 ha to over 43 ha. The total tundra area covered by pads and reserve pits in the Prudhoe Bay Unit as of 1983 is 1693 ha. Most of the Prudhoe Bay pads are over 1.8 m thick to prevent subsidence due to thaw of the permafrost zone. They are constructed of gravel hauled from one of the rivers or open pit mines. Elsewhere in northern Alaska, pad and road construction materials range from sands to crushed rock. Sometimes the pads are constructed with rigid polyethylene insulation under them to reduce the amount of gravel needed to insulate the original ground surface; if the pad is temporary, only a thin layer of gravel or sand is commonly used.

Many of the disturbances associated with pads are similar to those caused by roads, including an alteration of the tundra's thermal regime and the impoundment of water caused by blockage of natural drainage patterns (Fig. 25). Activities on the pads account for numerous other types of disturbances, such as noise pollution and contaminants from leaking reserve pits and sewage treatment areas. Maps of one highly developed 20.9-km area within the field show that thermokarst pit terrain has increased from 134 ha in 1949 to 193 ha in 1983 (Walker et al. 1986).

The problems associated with permanent facilities such as those at Prudhoe Bay are quite different than with thin temporary pads, which eventually are revegetated. If the industrial complex is abandoned, leveling and revegetation of the pads may be required. The pads are hostile environments for plants, and artificial revegetation would be expensive. Organic carbon is all but absent (< 1%), and there are few exchangeable nutrients in the coarse river gravels. Such sites have been

* Prepared by D.A. Walker and K.R. Everett

a. 1968.



b. 1980.

Figure 25. Portion of the Prudhoe Bay oil field before and after development.

created from unweathered coarse gravel, in which particles smaller than 2 mm make up less than 10% in the upper 5 cm. Some of the older pads that have been abandoned at Prudhoe Bay have developed very sparse vegetation communities with some of the same taxa that grow on gravel river bars (Table 3). At Cape Thompson, revegetation after 17 years shows a considerably richer flora with a high cover of grasses, mainly *Deschampsia caespitosa* (Table 4). This is likely due to a somewhat warmer summer climate and a longer period of recovery at Cape Thompson than at the Prudhoe Bay site. Some pads have been revegetated farther south at abandoned pipeline camps, but revegetation has been less successful near the arctic coast. The small amount of summer warmth

(about 450°C thawing degree-days) at Prudhoe Bay limits the amount of growth that can occur.

Temporary pads that have been constructed in areas with frequent natural disturbances, such as flood plains, are more quickly revegetated because of local seed sources that are capable of colonizing river gravels. In hydraulically active flood plains, some roads and pads have completely vanished within 15 years because of natural river activity.

Table 3. Taxa naturally colonizing a well site (BP Put. R Well) 10 years after abandonment. This is one of the older pads in the region, constructed in 1970, and has been one of the least disturbed since drilling (Walker 1985).

Arctagrostis latifolia	*Epilobium latifolium**
Artemisia borealis	*Eutreme edwardsii*
Artemisia glomerata	*Festuca baffinensis*
Astragalus aboriginum	*Lloydia serotina*
Astragalus alpinus	*Oxytropis nigrescens*
*Braya pilosa**	*Papaver lapponicum*
Bryum spp.	*Parrya nudicaulis*
Cerastium beeringianum	*Polemonium boreale*
Draba alpina	*Saxifraga oppositifolia**
Draba lactea	*Trisetum spicatum*

* These taxa are particularly abundant.

Pads constructed on the open tundra, however, are likely to remain unaltered for many hundreds of years and for all practical purposes represent a permanent change to the environment.

At the new test well sites in NPR-A, which were drilled and abandoned in 1976, drill pads, runways and roads have been artifically revegetated. This was generally more successful in the southern portions of the coastal plain. Considerable vegetation cover was observed between 1977 and 1982 at sites that were reseeded and fertilized repeatedly. For example, at the Inigok drill site in 1982, 600 lb/acre of fertilizer were applied, and most of the drill pad now has a considerably greater cover of nonnative grasses than it had in 1980. Weedy dicotyledonous taxa occasionally appear but are transient. Native plants seldom appear to colonize within stands of grasses from the artificial seed mixture. The best development of artificial vegetation cover occurs in depressions on the pads where there is more available moisture. The Teshekpuk Test Well drill pad, which was elevated and dry, had to be leveled to enhance plant growth. At Cape Thompson there were no revegetation attempts on old runway and pad surfaces. The list of colonizers in Tables 3 and 4 are mostly natives and could provide a list of candidate species for devel-

Table 4. Vegetation on abandoned gravel runways at Cape Thompson, Alaska, a foothills site (Everett et al. 1985). The runway has been used only sporadically since 1963.

Primary species	*Secondary species*	*Trace*
Deschampsia caespitosa	*Antennaria friesiana*	*Cochlearia officinalis*
Festuca brachyphylla	*Arctagrostis latifolia*	*Salix alaxensis*
Poa glauca	*Artemisia arctica*	*S. pulchra*
P. pseudoabbreviata	*A. glomerata*	
Sagina nivalis	*A. tilesii*	
	Carex microchaeta	
	Castelleja caudata	
	Cerastium beeringianum	
	Descurainia sophioides	
	Douglasia ochotensis	
	Draba palenderiana	
	Epilobium latifolium	
	Festuca rubra	
	Elymus mollis	
	Luzula confusa	
	L. kjellmaniana	
	Minuartia arctica	
	M. elegans	
	M. macrocarpa	
	Oxytropis nigrescens	
	Poa lanata	
	Potentilla hyparctica	
	Puccinellia vaginata	
	Salix glauca	
	Trisetum spicatum	

oping native seed mixtures for harsh arctic sites. Especially good candidates include *Epilobium latifolium, Braya pilosa, Deschampsia caespitosa, Festuca brachyphylla, F. rubra, Artemisia* spp., *Trisetum spicatum, Astragalus alpinus, A. aboriginum* and *Oxytropis nigrescens.*

*Gravel borrow pits.** Most gravel borrow areas in the coastal plain either fill with water, forming channels within a year or two to form natural-appearing river gravel bars. In contrast, upland gravel borrow areas in the foothills vegetate naturally very slowly. Most of these gravel surfaces are hostile environments for plant growth. Both nutrients and moisture are frequently limiting, but unlike roads, the sites are rarely elevated above the general tundra surface, so revegetation is somewhat easier (Johnson 1981). If fine-grained material is placed over the gravel, the areas can be usually be revegetated.

Because of the large amounts of gravel required for thermal insulation of roads and pads, gravel borrow pits may cover extensive areas. During the construction of TAPS there were more than 78,500 ha of land disturbed; 30,000 ha, or 38%, was for gravel borrow sites, with an additional 1,700 ha for disposal sites that were originally used as gravel pits (Pamplin 1979).

Permanent roads.† There has been considerable discussion and research regarding the effects of permanent roads in the arctic (e.g. Berger 1977, Pamplin 1979, Brown and Berg 1980, Johnson 1981). The physical disturbances related to roads include elimination of habitat beneath the roadbed, dustfall (Everett 1980, Spatt and Miller 1981, Klinger et al. 1983), roadside erosion and thermokarst development (Berg 1980), impoundments (Klinger et al. 1983), roadside trash, and deposition of plowed material and gravel on the adjacent tundra. The roads also act as corridors for the migration of weeds into the Arctic (Johnson and Kubanis 1980, Kubanis 1980). Perhaps the greatest long-term effect is the access that the roads provide to vast areas of undisturbed tundra and the additional pressures placed on wildlife populations (Cameron 1983, Smith and Cameron 1985).

The Prudhoe Bay road network is the most extensive in the North American Arctic and spans the Prudhoe Bay and Kuparuk oil fields (Fig. 26). The total length of roads was 506 km in 1983. The first roads in the region were built on thin gravel pads (Fig. 27), but these subsided because of thawing beneath the road surface. Later roads were built on gravel pads up to 2 m thick. Approximately 700 ha of tundra have now been covered by roads. Road-related impacts affect a greater area. For example, within the Prudhoe Bay oil field, which has 348 km of road covering about 480 ha, there are about 1380 ha of construction-related impoundments. Areas affected by other road-related disturbances such as dust and thermokarst processes are more difficult to calculate but are mostly limited to about 100 m on either side of the road.

* Prepared by L. Johnson.

† Prepared by D.A. Walker and K.R. Everett.

The Spine Road is the main transportation artery through the Prudhoe Bay oil field and has had heavy travel on it for the past 15 years. Areas along this road provide examples of impact that can be expected adjacent to other heavily traveled roads on the coastal plain. Impoundments and road dust are the most extensive road-related physical impacts at Prudhoe Bay. The severity of these impacts varies considerably depending on the manner of road construction, the local vegetation, the ground ice volume, the terrain relief and the amount of traffic.

*Roadside impoundments.** Along the Dalton Highway (Fig. 1), which parallels the major drainage of the Sagavanirktok River, most of the road-related flooding occurs upslope of access roads to material sites (Berg 1980). Within the Prudhoe Bay region, most instances of flooding occur where the road crosses low-lying, vegetated, drained thaw-lake basins. The West Road is a 7.0-km road, constructed in 1980–81 through one of the flattest, wettest portions of the Prudhoe Bay oil field. This road (Fig. 28) produced 134 ha of flooding (18 ha/km or 75 acres/mi) (Klinger et al. 1983). Most of the flooding occurred on the southeast upslope side of the road in drained thaw-lake basins. The most notable effect during the first two years of monitoring was a greening of vegetation in the flooded areas. Over 90% of the flooding was confined to wet and aquatic tundra vegetation. Most of this flooding does not last all summer, so it does not cause major damage, although the plant communities have changed.

The vegetation is occasionally killed in areas of prolonged and deep flooding. Moist microsites, such as polygon rims, hummocks and strangmoor, are important habitats for nesting birds and are often eliminated in the flooded areas during the nesting period. The vegetation on these moist sites is likely to show major changes, with mesic tundra species replaced by more hydrophilous taxa such as *Carex aquatilis* and *Eriophorum angustifolium.*

* Prepared by D.A. Walker.

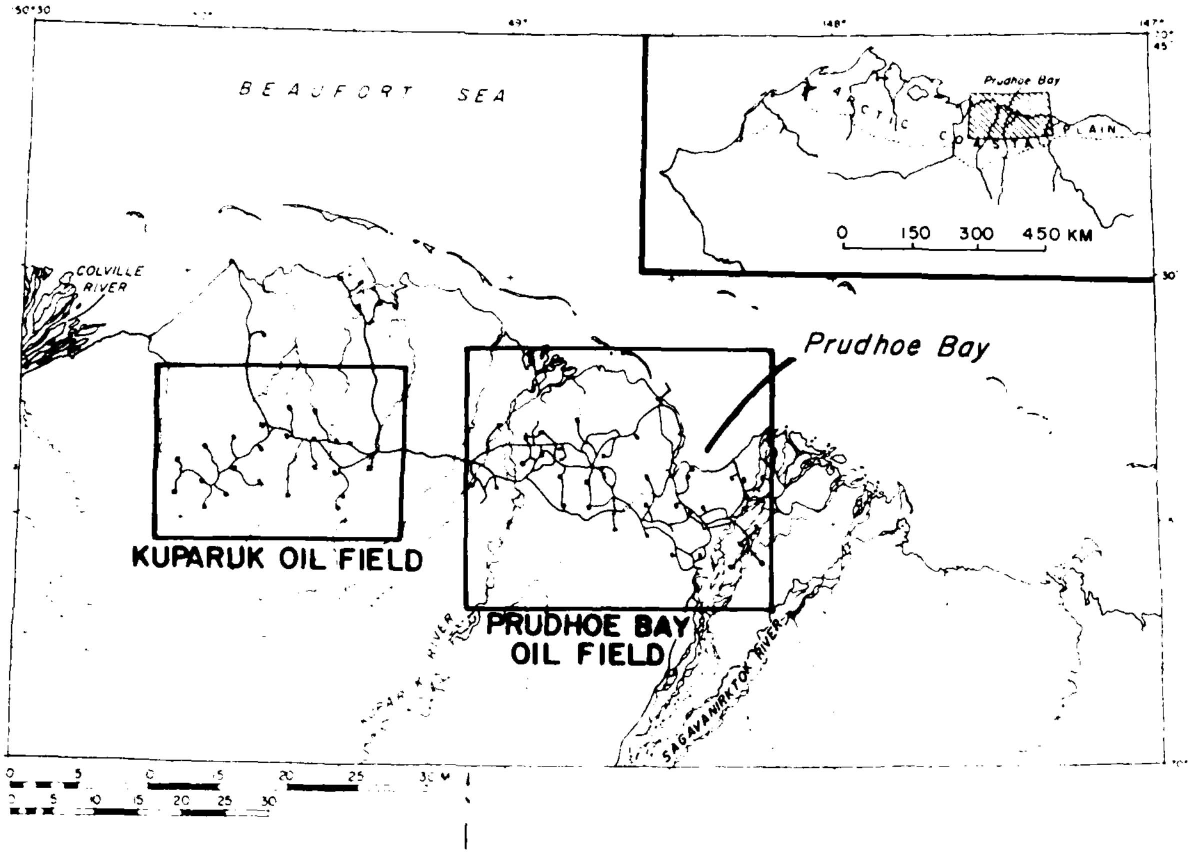


Figure 26. Location of the Prudhoe Bay and Kuparuk oil fields and the associated road network.

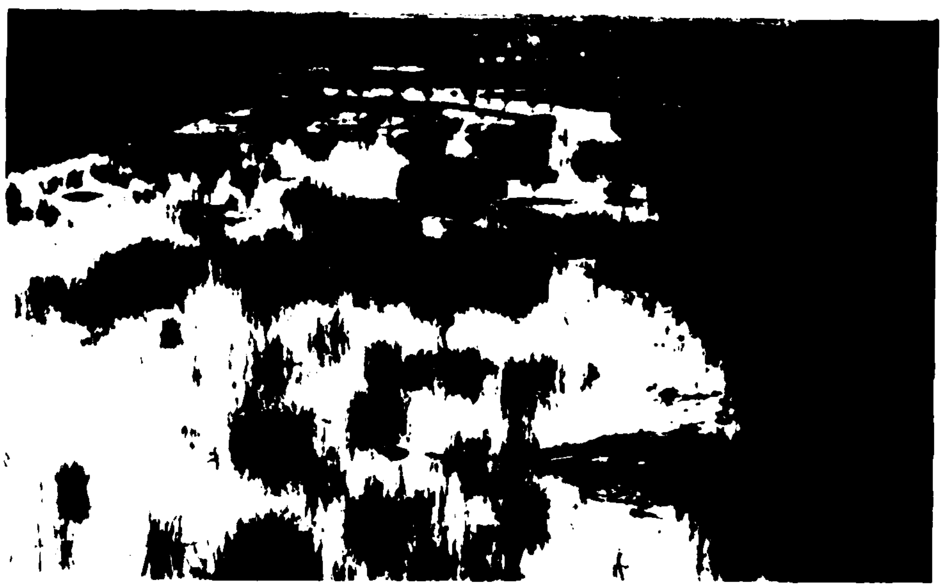


Figure 27. Early gravel road constructed in the late 1960s with insufficient gravel to prevent thermokarst. In places the road surface has subsided to the original ground level. (Photo by K.R. Everett, July 1983.)

Figure 28. Flooding in a drained lake basin along a road in the Prudhoe Bay region. The photo was taken in early summer before the ice in the culverts thawed. By late summer the large semicircular impoundment drained, but the vegetation became noticeably greener in this area. Also note the other impoundments along the road leading into the background. The largest of these (arrow) does not drain all summer. (Photo by L. Klinger, 21 June 1982.)

Culverts blocked by snow and ice increase the area of flooding and prolong the flooding period. In areas with an intersecting web of roads, flooded areas are more common and are often extremely difficult to drain. Drainage patterns on the flat tundra are complex, and there are many unconnected drainage systems. Detailed hydrology maps and observations during melt-out are helpful in deciding where to place culverts.

Another form of flooding occurs in narrow strips along the margins of most Prudhoe Bay roads. This type of flooding is accentuated if the ground subsides, either when the road settles or when areas adjacent to the road thaw. Numerous roadside areas along the Spine Road are covered by thermokarst features flooded 30-100 cm deep above thawed ice wedges (Fig. 29). The thermal disturbance results from the flooding and the loss of vegetation buried by road dust. High-centered polygons are a common result of thermokarst. At Prudhoe Bay, thermokarst features occur mostly within 25 m of the road, but in some areas thermokarst is actively expanding into the tundra at distances of up to 100 m from the road.

*Road dust.** A thorough understanding of the effects of both natural and road-generated dust is important for designing roads, selecting transportation corridors and implementing dust control methods (e.g. Techman Engineering Ltd. 1982). Road dust on arctic tundra (Fig. 30) is a relatively

* Prepared by K.R. Everett and D.A. Walker.

Figure 29. Roadside environment along the Prudhoe Bay Spine Road. Note the barren area caused by dust and water-filled ice-wedge polygon troughs. High-centered polygons have formed since the road was built in the 1970s. (Photo by D.A. Walker, 16 Aug 1983.)

Figure 30. Road dust along the Spine Road at Prudhoe Bay. Note the thermokarst on the south side of the road, which is the side normally receiving the greatest dust loads due to the dominant winds from the east-northeast. (Photo by K.R. Everett, 1981.)

recent phenomenon, and several studies were undertaken of the effects of dust on tundra vegetation (Spatt and Miller 1979, Everett 1980, Werbe 1980, Klinger et al. 1983, Walker et al. 1985a). During the winter when the roadbed is frozen, evidence of dust is not obvious; however, as the road surface thaws and dries, dust becomes more apparent. Snow-covered areas on the downwind side of the road begin to melt earlier than on more distant terrain. Dust is visible on winter Landsat images of the Prudhoe Bay region (Benson et al. 1975). Melt occurs about 10–14 days earlier in roadside areas and extends 30–100 m from heavily traveled gravel roads. Dust has caused nutrient enrichment in lakes of the Prudhoe Bay region (Bilgin 1975) and Toolik Lake in the foothills (Spatt and Miller 1979).

Everett (1980) measured dustfall and wind along the Dalton Highway and the Spine Road. He found that dust loads decrease logarithmically away from the road, and the amount of dust is closely related to the prevailing wind direction. Summer dust loads exceeded 5 kg/m^2 at 8 m from the road at Prudhoe Bay, Franklin Bluffs and Sagwon in 1978 (96 collection days). Near Deadhorse, dust loads 1000 m from the road were several times higher than at similar distances from the road at other sites. This was thought to be an effect of the dense road network at Prudhoe Bay with road dust coming from many sources. Dust loads during the rest of the year contributed an additional 1–1.5 kg/m^2 at sites 8 m from the Dalton Highway. Along the more heavily traveled Prudhoe Bay roads, the nine-month winter dust volumes were about the same as the three-month summer volumes near the road; at 312-m collection stations, winter dust fall was nearly 10 times greater than in the summer. The winter data also showed more scatter from the usual logarithmic distribution downwind from the road. These summer–winter differences are probably due in part to repeated drifting and erosion of the snowpack and the easier transport of dust across snow than across wet vegetation. There is a rapid decline in mean particle diameter in the first 8 m from the road. The decrease is from coarse sand (0.5–1 mm) to near the upper limit of coarse silt (50 μm). A further, but much less significant, decline in mean particle diameter is noted at 30 m. Beyond 30 m to at least 312 m there is little significant change in mean particle size of the dust, with most of it being 50–20 μm in diameter (coarse silt). The total amount of available soil cations in the upper 2.5 cm has increased on the west side of the Dalton Highway due to dust.

Road dust, like its natural counterpart loess, is alkaline, with calcium and magnesium the most abundant basic ions. Throughout the foothills and in much of the taiga area south of the Brooks Range, the alkaline dust falls on an acid tundra. Over the five years of Everett's study, the normally high buffering capacity of this tundra, which is due to large amounts of exchangeable hydrogen and aluminum, was neutralized in some areas. In the upper 2–5 cm the soil pH has shifted from acid to alkaline. A less dramatic and somewhat erratic build-up of other cations, such as potassium, was also documented. Soil chemical changes induced by road dust were measurable only after three or more years of impact in the zone of high dust impact (0–30 m). Changes in areas of lower dustfall will take much longer to become recognizable.

The physical and chemical effects of road dust on vegetation have been difficult to document because of the complex interaction of numerous roadside impacts (e.g. ponding and warmer soil temperatures), but with the bryophytes the case is clear: a significant reduction and often elimination of *Sphagnum* moss, especially in the 0–10 m adjacent to the road (Spatt 1978, Spatt and Miller 1981, Werbe 1980, Walker, unpub. data). This is caused by the toxic effects of calcium in the dust (Clymo 1973) and reduced photosynthetic rates in the moss of heavily dusted areas (Spatt and Miller 1981). Observations in 1983 (Walker et al. 1985a, Spatt, unpub. data) showed that in many areas of *Sphagnum*-rich tundra, *Sphagnum* has indeed been eliminated but was at least partially replaced by mosses such as *Ceratodon purpureus, Bryum* spp. and *Polytrichum juniperinum*. The insulation values of these new mosses, however, are nowhere near that of *Sphagnum*. Other plant species also react negatively to road dust (e.g. *Cassiope tetragona* and *Cladonia*), but some, especially several moss species (e.g. *Drepanocladus, Scorpidium* and *Catascopium*), seem to respond positively to the increased nutrients.

In some areas along the most heavily traveled roads at Prudhoe Bay, all vegetation has been totally eliminated within 5 m of the road (Fig. 29), with mosses eliminated to distances of about 20 m. Beyond about 100 m, the vegetation, although heavily dusted, appears to survive with little compositional change. The loss of vegetation near the road is at least partially responsible for the extensive thermokarst features that have developed along the older roads (Fig. 29).

The changes at Prudhoe Bay are occurring in a tundra that is already well adapted to high influxes of natural dust (loess) (Walker 1985). If a develop-

ment of the magnitude of the Prudhoe Bay oil field occurred within acidic tundra regions, the changes are likely be much more extensive because acidophilic tundra species near the road will be eliminated in high dust areas.

Contaminants

Contaminants are often spilled on the tundra during exploration and development. These substances contain a wide range of chemicals, many of which are toxic to plants. Some common contaminants include drilling mud, wastewater, reserve pit fluids, used crankcase oil, dust control chemicals, diesel fuel, crude oil, and salt water. The last three have been studied by CRREL-sponsored research and are summarized here.

*Hydrocarbon spills.** During the early exploration of NPR-A and more recently during the construction of the Dalton Highway and the pipeline, there have been numerous spills of both crude and refined petroleum products. At the Fish Creek site, crude oil, crankcase oil and diesel fuel spills occurred between 1948 and 1949. From 1974 to 1977 during the construction and initial operation of the trans-Alaska pipeline, more than 16,000 oil spills occurred along the pipeline route (Johnson 1981). These spills totaled more than 2,650,000 L (700,000 gal.), most of which were refined petroleum products. Although many of the spills were in water or confined to gravel pads, some occurred on terrestrial vegetation.

Large spills of crude oil from the pipeline are rare but have occurred at least five times from 1974 to 1977. The largest spill on the North Slope occurred at valve 7 (AS 133) north of Franklin Bluffs, where over 300,000 L (80,000 gal.) of crude oil was sprayed over an area of 8.3 ha of primarily wet sedge tundra (Walker et al. 1978, Johnson 1981). The spill resulted from a ruptured valve, and oil sprayed a considerable distance into the air. The oil was carried over 1200 m downwind, and an area within 250 m of the valve was heavily coated with oil. Workers cleaned up the spill by digging ditches by hand through and around the spill area to collect the excess oil, which they removed with suction pumps (Johnson 1981). The clean-up efforts caused major impacts, with repeated trampling and churning of the oil- and water-saturated tundra by the workers. As a result, it was difficult to distinguish between oil-induced and trampling-induced damage.

The recovery of soils and vegetation following oil spills has been thoroughly reviewed elsewhere (i.e. McCown et al. 1973, Wein and Bliss 1973b, Deneke et al. 1975, Mackay and Mohtadi 1975, Freedman and Hutchinson 1976, McGill 1977, Everett 1978, *Arctic*, vol. 31, no. 3, 1978, Johnson et al. 1980, Linkins et al. 1984). Most recent work and observations of long-term recovery at old spill sites has confirmed several general observations.

The distribution of the spilled hydrocarbon from the spill point greatly affects vegetation recovery. The spill distribution is governed by character of the spill (point vs spray), pour point temperature, roughness of the surface, snow cover, whether or not the surface is frozen, slope and porosity of the surface. Hydrocarbons spilled on snow or at very low temperature may be immobilized quickly. Spray spills may allow many of the lighter, more toxic fractions to evaporate before reaching the ground.

Recovery following diesel spills is extremely slow. On dry sites there was evidence of wind erosion because of the lack of vegetation. At Fish Creek, 28-year-old diesel spills showed little vegetation recovery, significant depression of the permafrost, deeper thaw beneath the spill, and strong diesel odors to at least 40 cm deep in the soil. Gas chromatography showed that there was still a toxic component in the soil after 28 years (Everett 1978). In contrast, spills of crankcase and crude oil showed good recovery after 28 years, except in the areas of heaviest impact. At Prudhoe Bay the recovery from crude oil and diesel spills was generally poor in dry and moist sites after seven years, but a few taxa were colonizing the spills. In aquatic sedge tundra sites there was good recovery of sedges and moss on the oil spill but virtually no recovery on the diesel spill (Walker et al. 1985b).

There are general trends of recovery related to site moisture. Spills on saturated soils or areas with shallow standing water will disperse quickly as a film from which volatiles are lost. Oil does not penetrate deeply in saturated soils, but spills on dry sites are absorbed by mosses and underlying organic material and may even penetrate into the mineral soil. Linkins and Fetcher (1983) recorded 123 L/m^2 of crude oil absorption. The toxic volatiles are released very slowly in these spills, and the microbial decomposition may take decades. Light spills on wet sites may recover completely within a year or two.

Some components of the vegetation are more susceptible to oil-spill damage. The most easily killed are the mosses and lichens. These also may be the first to recolonize the spill, but the colonizing moss taxa are generally different from those in the nonimpacted areas. Sedges and willows are the

* Prepared by D.A. Walker, L. Johnson and K.R. Everett.

first vascular plants to reappear following oil spills. At Prudhoe Bay there was regrowth of some sedges one year after a 12-L/m² oil spill, but seven years after the spill there was very little vascular plant cover in either the moist or dry spill areas. At a more southern site near Fairbanks, tussock cottongrass regrew despite oil-saturated soils in the root zone (Johnson et al. 1980). In the aquatic sedge tundra, sedge cover had returned to prespill values (Walker et al. 1985b).

The effects of oil spills on permafrost are highly variable. Several investigators have reported that the depth of seasonal thaw in areas of oil spills differs little from nonimpacted areas (Freedman and Hutchinson 1976). However, at the Franklin Bluffs site there was a marked difference in thaw six years after the spill. Within 80 m of the spill point, thaw increased to over 100 cm, whereas the thaw depth in undisturbed sites was 46 ±7.8 cm. Subsidence was apparent in a few areas, but it was not severe, mainly because the entire spill area is underlain by thick alluvial gravels (Walker et al. 1985b).

Maps of the sensitivity of vegetation to oil spills have been produced based on the resilience of individual plant taxa making up the plant communities at Prudhoe Bay (Walker et al. 1978). This approach is valid for spill conditions similar to those of the experimental studies and for the range of communities tested. However, there are numerous common tundra plant communities for which we have no information about their response to oil spills.

*Seawater spills.** Secondary recovery of oil at Prudhoe Bay involves transporting large quantities of seawater in elevated pipelines across the tundra for injection into oil-bearing strata. Simmons et al. (1983) examined the changes to vegetation and soils associated with seawater spills in acidic and alkaline dry, moist and wet tundra sites at Prudhoe Bay.

There was an inverse relationship between soil moisture regime and the absorption and retention of salts. In wet sites, conductivities approached prespill levels within 30 days; the salt water was quickly diluted and flushed from the soil. In contrast, the dry sites tended to retain the salts, concentrating them at or near the seasonal thaw line. Ectomycorrhizal roots of *Salix rotundifolia* in seawater-treated areas showed significant reductions in number, viable biomass and respiration rates for viable roots.

Recovery of vegetation on the spill sites after three years appears to be related to the pH of the site. Alkaline dry and moist sites show less recovery than similar sites in acidic tundra. In acidic tundra the most affected taxa (forbs, shrubs and mosses) showed strong recovery within three years following the spill. In alkaline sites the recovery was much less pronounced, although most taxa were beginning to return. Wind erosion was becoming a problem three years after the seawater spill on the dry alkaline sites. Saturating applications of seawater created visible symptoms of stress in 30 of 37 taxa of shrubs and forbs, while none of the 14 graminoid taxa showed adverse effects. One year following the spills, live vascular plant cover was reduced by 89-91% in dry sites and by 54-83% in the moist sites; vascular plants in wet sites were unaffected. The number of vascular plant taxa was reduced by 20-73% in the moist and dry sites, while none were eliminated in the wet sites. Bryophytes were also much reduced in dry and moist sites.

Salt is a constituent of a variety of contaminants. It is the primary toxic element in old reserve pit fluids. Work conducted by the oil industry (Myers and Barker 1984) has shown that the toxicity of these fluids varies considerably. Salt concentrations within pits vary through the summer. They tend to decrease with the age of the pit because they become diluted by snow. Myers and Barker (1984) also found that the breakpoint between damage and no damage to the most salt-sensitive tundra (dry dwarf-shrub, crustose-lichen tundra) was between 2000 and 4000 mg/L of total dissolved solids.

TOWARD AN ECOLOGICAL UNDERSTANDING OF DISTURBANCE AND RECOVERY IN ARCTIC TUNDRA ECOSYSTEMS

The processes of recovery in disturbed ecosystems are extraordinarily complex. In this section, we review recovery of the physical and vegetation components of the ecosystem in light of current ecological hypotheses, and then we examine the problem of cumulative impacts.

Physical recovery*

The development of physical stability is a prerequisite for vegetation recovery. Without that

* Prepared by K.R. Everett.

* Prepared by D.E. Lawson.

stability, vegetation cannot fully establish itself. The time required to attain a physically stable ground surface may vary within a site as well as across a region because of a number of factors.

The analysis of the physical properties of substrate materials at disturbed sites in NPR-A indicates their importance in both spatial and temporal variations of impact. Particularly important are the ground-ice volume, the presence and size of massive ice, the thawed strength of sediments, and the relief of the disturbed area and how it changes with time. Long-term physical modifications are greatest in terrain that is underlain by high-ice-content, fine-grained sediments and that has sufficient relief to permit the meltwater to run off as the permafrost thaws. Low-relief areas underlain by sand-sized material of lower ice content are least modified. Lateral expansion of modifications beyond the area of a surface disturbance expands laterally when the exposed, thawing sediments are in slopes that are susceptible to failure.

Data from two sites in NPR-A (Table 5) contrast the properties of ice-rich, fine-grained sediments (East Oumalik) and relatively ice-poor, coarse-grained sediments (Fish Creek). These data indicate that the sediments at East Oumalik are generally unstable at thaw. In contrast, the sands at Fish Creek clearly have significant frictional resistance to shear. The water contents of the sands remain well below the liquid limits, and they are generally unsaturated. Similarly the granularity and relatively high porosity of the material suggest that pore pressures will not significantly increase during thawing. Ice composes 35% or more of the volume of the sediments in the upper 5 m at East Oumalik than at Fish Creek. Also, massive ground ice composes only an estimated 20–25% of the upper 5 m of the Fish Creek materials, whereas it composes more than 65% at East Oumalik; this difference results from the smaller ice wedges and the absence of ice lenses and layers at Fish Creek.

The greater initial relief at East Oumalik plus the relief that developed during thaw subsidence were sufficient to produce slumping and hydraulic erosion leading to severe erosion. In the flat landscape at Fish Creek, however, thermal and hydraulic erosion were active mainly in drainage ditches and bulldozed trails located on the few slopes at the site.

An index of the severity of disturbance S_i is useful for comparing the physical effects between sites:

$$S_i = A_{fd}/A_{id}$$

where A_{fd} is the final area of impact and A_{id} is the initial area of disturbance. The disturbed area is defined as an area initially affected by some disturbance, for example the narrow wheel-width tracks left by a wheeled vehicle. The final area of impact is that which is physically modified in response to the initial disturbance. For S_i = 1.0, the

Table 5. Selected properties of near-surface sediment from undisturbed and disturbed locations at the East Oumalik and Fish Creek drill sites. (From Lawson 1982.)

	East Oumalik upland		*Fish Creek upland*	
	Undisturbed	*Disturbed*	*Undisturbed*	*Disturbed*
Grain-size (φ), mean (m), std. dev. (δ)	m - 5.50 δ - 1.2	m - 5.50 δ - 1.2	m - 2.75 δ - 0.7	m - 2.75 δ - 0.7
Moisture content (% dry wt)	80 to 250	40 to 120	19 to 71 (sporadically to 120%)	22 to 28
Ice volume (%) (excludes ice wedges)	60 to 100 (m - 85)	40 to 65	23 to 68 (m - 47)	33 to 42
Degree of saturation (frozen)	0.95 to 1.2 (m - 1.05)	0.8 to 1.1	0.6 to 1.05 (m - 0.96)	0.6 to 1.0
Bulk density (g/cm^3)	0.9 to 1.6 (m - 1.2)	1.6 to 1.8 (m - 1.65)	1.5 to 2.2 (m - 2.0)	1.8 to 2.1 (m - 2.0)
Dry density (g/cm^3)	0.3 to 1.1	0.8 to 1.2	1.4 to 1.8	1.5 to 1.8
Void ratio	3 to 14	0.5 to 2.8	0.4 to 1.61	0.4 to 0.78
Liquidity index	1.6 to >15	0.9 to 1.2	-1 to 0.5	-1 to 0.3

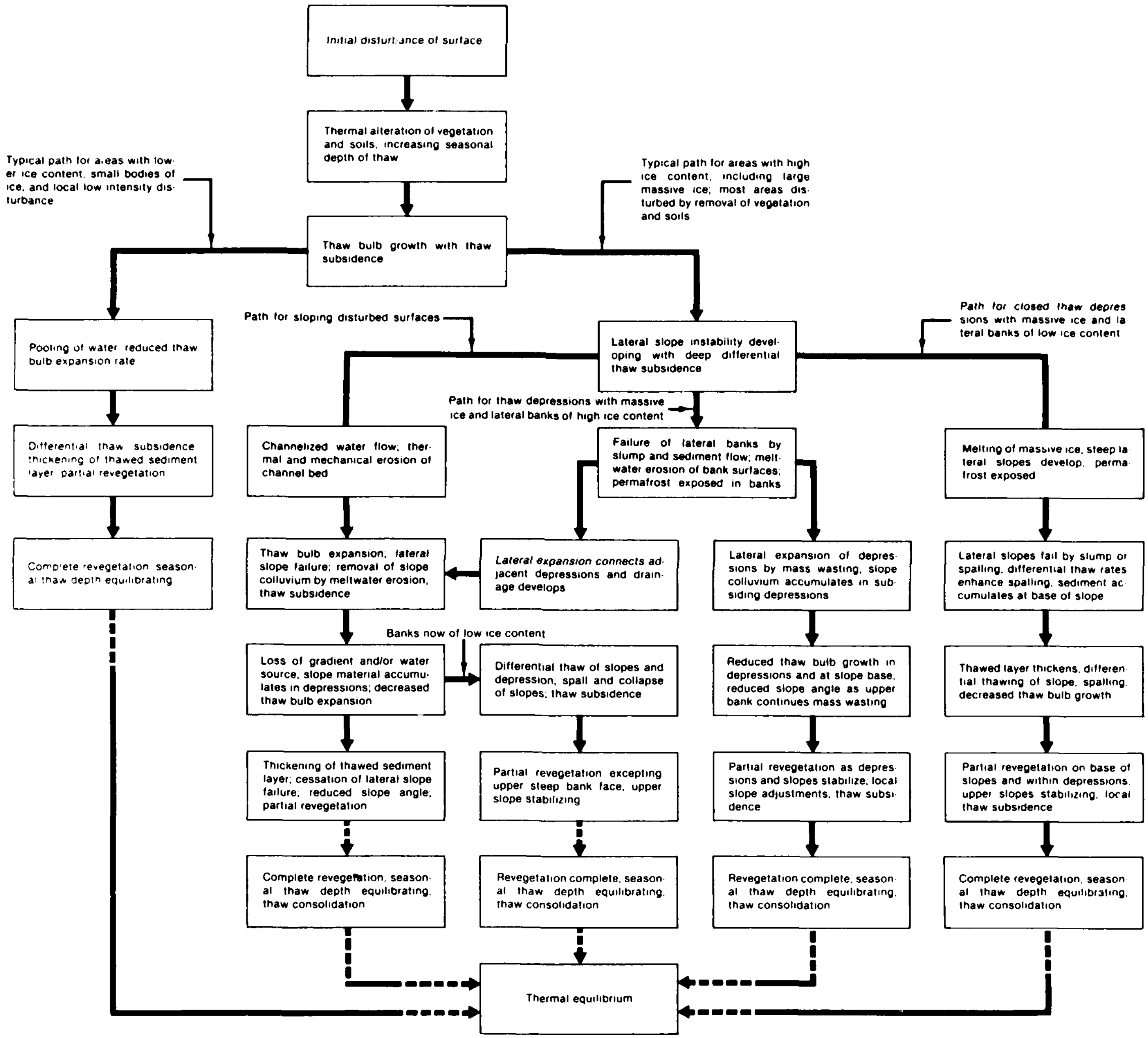


Figure 31. Common sequences of processes that caused the modifications of the East Oumalik site. The changes in vegetation are based upon flow charts of Bliss (1970) and Komárková and Webber (1978). The physical effects are expanded and modified from a flow chart of MacKay (1970). The dashed line indicates steps that are not completed at East Oumalik. (From Lawson 1982.)

Table 6. Physical modifications to terrain at East Oumalik (EO) and Fish (FC) drill sites due to disturbances listed by groups (Table 2). S_i represents areal effects and is defined in the text. (Modified from Lawson 1982.)

Initial disturbance	*Site*	S_i *(Severity index)*	*Depth of depressions (m)*
Trampling or compaction of original vegetation	EO	1.1 to 1.43	0.7 to 4.2
	FC	1.0	0.1 to 0.7
Killing of original vegetation	EO	0.9 to 1.1	0.1 to 1.1
	FC	0.9 to 1.0	Up to 0.2
Removal of vegetation mat	EO	1.7 to 2.6	3.1 to 5.5
	FC	1.0 to 1.2	0.2 to 1.5
Removal of near-surface sediment with vegetation mat	EO	1.25 to 2.5	3.0 to 5.0
	FC	1.0 to 1.2	0.4 to 2.0

impacted area equals the area initially disturbed. For $S_i > 1.0$, the impact of disturbance has spread beyond the area physically disturbed. Values of $S_i < 1.0$ indicate that the effect of disturbance was not permanent, and the area is returning to its previous condition.

In Table 6, values for S_i at Fish Creek and East Oumalik are compared for the four general types of disturbances (Table 2). Typical depths of depressions resulting from subsidence and erosion are also listed. S_i values measured at East Oumalik (0.9 to 1.6) were generally larger than those at Fish Creek (0.9 to 1.2). At both sites, removal of vegetation and soil had the most severe impacts. The area of disturbances tended to increase at East Oumalik, but at Fish Creek it often did not. Similarly, the depressions are deeper and the increase in relief is much greater at East Oumalik than at Fish Creek.

When the vegetative mat or the upper mineral substrate is removed, the timing and mechanisms of recovery vary with the susceptibility of the terrain to disturbance. Disturbances in ice-rich terrain with fine-grained soils and substantial relief require the longest time to establish physical and thermal stability.

Physical stability depends on stopping the thaw depth from increasing after a surface disturbance; this means thickening the insulating cover. Reducing the thaw rate, increasing the stability, and reestablishing vegetation go hand-in-hand. Biological recovery proceeds where the uppermost sediments are not susceptible to erosion or to rapid and extensive subsidence. Figure 31 shows the typical sequences of events as disturbed tundra returns to thermal equilibrium.

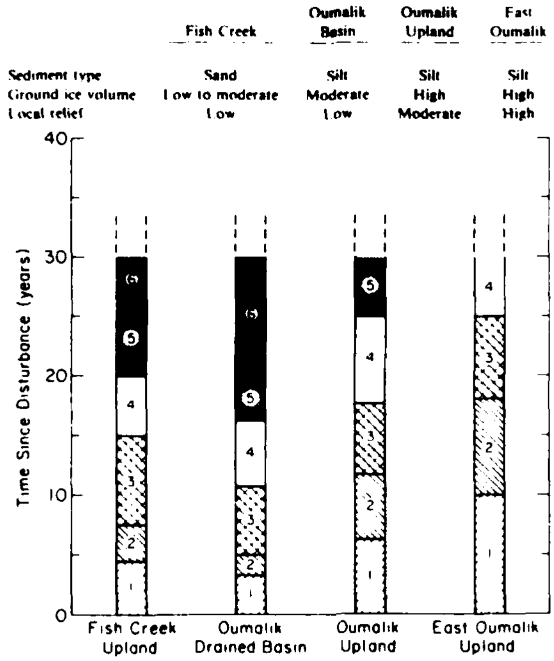


Figure 32. Rates of return to physical stability after disturbances at arctic coastal sites. Time spans vary as a function of the site relief, the sediment characteristics and the ground ice volume and distribution. The numbers refer to the following stages: 1) modification of thermal regime leading to increased thaw depths and thaw subsidence; 2) thaw subsidence coupled with hydraulic and thermal erosion, slope failure and mass movement; 3) stabilization of slopes with decrease in thaw depths and thaw subsidence; 4) thaw consolidation of sediments leading to physical stability; 5) physical stability but with thermal equilibration; 6) thermal equilibrium with the modified physical conditions maintained. (Lawson 1986.)

Several stages of physical modifications can be identified and, based on interpretation of older and recently disturbed sites, assigned estimates of time required to reestablish physical and biological systems (Fig. 32). This model lumps many parameters and thus only estimates the average rate of recovery for the entire site. It mostly considers areas where vegetation or soil are lost. Less intensely disturbed parts of a site exhibit each stage of recovery more rapidly, whereas a heavily disturbed location susceptible to continuing erosion will take longer to stabilize.

In summary, three factors appear to have the most influence on the intensity and extent of physical modifications, as well as the time required to attain physical and thermal stability: 1) the distribution of ice volume, which directly affects the mode and rate of degradation, 2) the physical properties of the sediments, which affect their susceptibility to failure once thaw begins, and 3) the local and regional slope, which affects moisture conditions, drainage and thus degradational processes.

Vegetation recovery

*Natural vegetation succession**

Natural processes of vegetation succession follow most disturbances to tundra ecosystems. The species that spontaneously colonize man-caused disturbances are generally the same that colonize natural disturbances. These opportunistic species have evolved dispersal mechanisms, physiological requirements and rates of growth that allow them to enter, establish and grow in open habitats. Bliss and Cantlon (1957) described the riparian successional sequences along the Colville River, and Billings and Peterson (1980) have described the sequences in thaw lakes near Barrow. However, thaw lakes and their successional patterns vary considerably along the coastal plain according to local substrate and temperature regime, and much more work is needed before the phytosociology associated with the various forms of the thaw-lake cycle are well understood.

Although the details of natural recovery are lacking for most northern Alaskan tundra communities, there are several general ecological principles that do apply. Some tundra communities are obviously more tolerant of, or resistant to, disturbance than others. Also, some of the most easily disturbed are sometimes the most resilient. This is not unique to the Arctic. Current plant ecology hypotheses state that mature, zonal vegetation (the climatic climax, occurring on soils with non-extreme conditions) is stable (i.e. resilient) only within a comparatively narrow range of conditions, whereas pioneering azonal vegetation (found in extreme soil conditions) is stable in a wider range of environmental conditions (May 1973, Goodman 1975). Moist tussock-sedge, mixed-shrub tundra is the zonal vegetation across much of northern Alaska. Typical azonal vegetation occurs in areas of extreme moisture conditions, such as wet drained thaw-lake basins. Frequently disturbed azonal communities in fluctuating environments are more resilient to catastrophic disturbances than similar communities in less-fluctuating zonal environments (Komárková 1983a). According to van der Maarel (1980), diverse zonal ecosystems occur in relatively constant environments and can develop a rich and constant assemblage of taxa. The simple azonal ecosystems, such as wet sedge tundra or sand dune communities, occur in rapidly changing environments and tend to develop poor and fluctuating assemblages of taxa.

Although wet tundra is easily disturbed, it recovers considerably faster than mesic uplands following a severe disturbance. The latter, in general, appear to be more resistant to an initial surface disturbance but less resilient following a major disturbance (Komárková 1983a). Thus, the initial response to disturbance (resistance) and the subsequent rate of recovery (resilience) of tundra vegetation are closely related to the site moisture conditions.

If a mesic upland surface is scraped, bryophytes such as *Marchantia polymorpha, Bryum* spp., *Ceratodon purpureus, Leptobryum pyriforme* and *Polytrichum* spp. usually will colonize the surface very quickly. This is usually true in moist tundra vegetation where a gap occurs in the plant canopy. The moss propagules are lightweight and always available, possibly in the seed bank. Bryophyte-dominated communities persist only in habitats that are not favorable for vascular plants, and they persist longest in the north. Also, in the north, lichens usually colonize the surfaces unavailable to bryophytes and vascular plants, such as dry surfaces of wood; in warmer areas they may also colonize dry, bulldozed soil surfaces.

Vascular plants are next in succession on mesic surfaces, and they are the first colonizers of most dry and wet surfaces. Taxa with rapid and efficient reproduction, dispersal, establishment and growth have an advantage. Annual and introduced weedy taxa usually are not important in the Arctic. In disturbed sites on zonal uplands, the

* Prepared by V. Komárková, J.J. Ebersole and P.J. Webber.

colonizing grasses *Arctagrostis* and *Poa*, which are not common in the surrounding natural communities, are dominant in the successional communities. These initial invaders spread by rhizomes and seedlings and inhibit the early development of *Eriophorum vaginatum* tussocks, which spread mainly by seedlings.

Areas that are wet after a disturbance are colonized mainly by sedges. On undisturbed mesic areas the most common plants are bryophytes and grasses. Willows are also important except near the coast. In the foothills *Eriophorum vaginatum* is an important colonizer. On dry areas colonization is much slower, and several grasses and forbs are the main colonizers.

It is, however, still difficult to generalize about successional patterns. For example, *Eriophorum vaginatum* does not appear to be an important colonizer at any of the sites observed in NPR-A, but it is an important colonizer at bare sites at Eagle Summit, Toolik Lake and the Seward Penninsula (Chapin and Chapin 1980, Chester and Shaver 1982). Ebersole (1985) did not find any *Eriophorum vaginatum* seeds in soils from Oumalik, but they were quite common in the soils near Toolik Lake (Gartner 1983, Roach 1983). A similar situation exists for *Calamagrostis canadensis*, which is a very important colonizer along much of the Dalton Highway and the Seward Peninsula but is infrequent in successional communities in NPR-A.

An important aspect of succession after disturbances is the relationship between the frequency of disturbances and the area they affect. Disturbances range from daily events, which often affect only a few square meters (such as needle ice and associated soil erosion), to events with recurrence intervals of millenia (such as sea level changes). A log/log relationship generally occurs between the recurrence interval of an event and the area it affects (Table 7). The majority of disturbances of interest in this report are severe disturbances with recurrence intervals of greater than a few years. The emphasis in disturbance ecology is likely to shift from the single disturbances that have been the subject of so much recent research to the topic of continual and accumulating impacts. The study of cumulative impacts will require a fundamentally different approach.

Table 7. Temporal and spatial scales of natural disturbance in Arctic Coastal Plain ecosystems.

Recurrence interval (years)	*Examples of disturbance events*	*Some ecosystem responses*	*Space scale (km^2)*
10^4-10^5	Global and regional climatic change; glaciation; formation of Arctic Coastal Plain; major sea level changes; establishment of regional drainage	Evolution of communities; shifts in dominant community types	10^2-10^3
10^3-10^4	Sand sea formation; thaw lake cycle; major changes in drainage patterns; fires; second and higher order drainage development	Soil formation; primary succession; succession to "climax"	10^1-10^2
10^2-10^3	Ice-wedge polygon formation, microtopography changes	Secondary succession and within-community changes	10^0-10^1
10^1-10^2	Regional and local climatic fluctuations; slope failures	Community adjustments	10^{-1}-10^0
10^0-10^1	Severe storms; extremes of weather; herbivore outbreaks; fires; storm surges	Community recovery within resilience threshold	10^{-2}-10^{-1}
10^1-10^{-1}	Seasonal weather patterns; annual hydrologic cycle; loess fall	Soil erosion; water stress; small adjustments within resistance threshold	10^{-3}-10^{-2}
10^{-1}-10^{-2}	Daily or hourly climate fluctuations; needle ice formation	Diurnal or hourly growth responses; seedling establishment; community maintenance; no directional changes	10^{-4}-10^{-3}

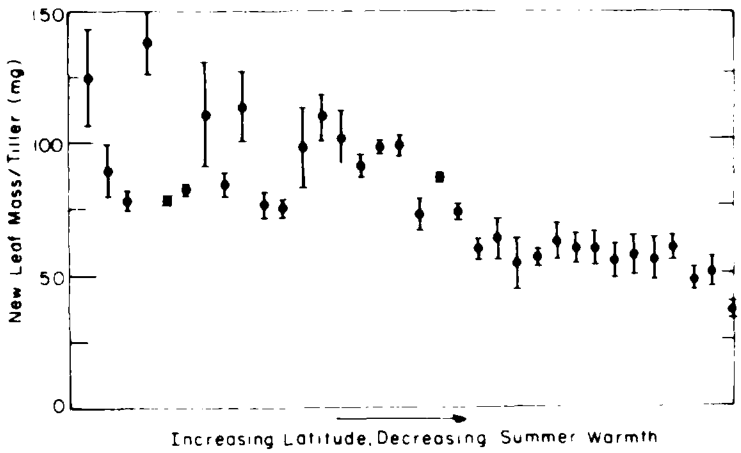


Figure 33. Leaf mass per tiller of Eriophorum vaginatum *along a transect from Smith Lake to Prudhoe Bay. The values are means with standard errors for 1980–1983. (Modified from Shaver et al., in press.)*

*Role of temperature.** Low temperature is undoubtedly the environmental factor most frequently cited as limiting for plant growth in these regions. Low temperatures are most likely to limit plant growth in the northernmost portions of Alaska, particularly for nonnative introduced species. Native plant species have both physiological and morphological adaptations that at least partially compensate for low soil and above-ground temperatures (Bliss 1962, Billings and Mooney 1968, Savile 1972, Chapin et al. 1979, Chapin 1983), while introduced species are frequently adversely affected (McCown 1973). Introduced species cannot absorb nutrients as readily in these cold soils. Permafrost limits the depth of the rooting zone and hence the volume of soil from which roots can absorb nutrients. Low soil temperatures also retard decomposition, so nutrient cycling is impeded, further limiting plant nutrient uptake, especially in permafrost areas. The shortness of the arctic and subarctic growing seasons is partially offset by the long summer photoperiod in the high latitudes. However, in these extreme photoperiods, most introduced plant species find it difficult to adapt to new light cycles in order to initiate such activities as flowering and winter hardiness at the appropriate times. The photoperiod differences, coupled with extreme winter conditions and sporadic midsummer freezes, decrease the chances of finding introduced plant species that will readily adapt to the Arctic and, to a lesser extent, the Subarctic.

* Prepared by G. Shaver.

Arctic plants have adapted to these environmental conditions by such features as high root-to-shoot ratios to facilitate nutrient uptake, extreme winter hardiness, prostrate growth forms to avoid snow abrasion in alpine and arctic areas, and reduced reliance on sexual reproduction (Billings and Mooney 1968, Savile 1972, Bliss 1979). These adaptations maximize the chances for long-term survival, but they are also important for revegetation.

In revegetated areas along the TAPS, native plant reinvasion has been disappointingly slow, and it has been difficult to determine the relative significance of such factors as low seed production by native species, physical or chemical inhibition of germination by litter or established plants, or competition by seeded grasses.

The growth and flowering of sheathed cottongrass (*Eriophorum vaginatum*) were studied along the latitudinal and climatic gradient of the Dalton Highway. The leaf weight per tiller of this species is roughly correlated with the amount of summer warmth along the transect (Fig. 33). There were two major discontinuities in the latitudinal gradient for both variables, one near the crest of the Brooks Range and the other at the transition from the arctic foothills to the coastal plain. The greatest variation between adjacent sites was south of the Brooks Range, where tillers were smaller in higher-elevation and extremely wet sites than in forested muskeg sites. The relationship between tiller size and latitude is genetically based (Shaver et al., in prep.). For variables such as flowering, there was no consistent latitudinal trend but very

large annual variation. Thus, plant growth seems well buffered against year-to-year climatic variations, but reproductive characteristics are more responsive to climate in a given year than to long-term average climate. In general, a heavy flowering year at one site is a heavy flowering year everywhere along the transect.

Dwarf shrubs, herbaceous dicots and taller shrubs play a greater role in the colonization process and in the successional vegetation in the south, particularly at sites where they are common in the surrounding undisturbed vegetation. The willows and dwarf shrubs are noticeably taller toward the southern part of the coastal plain, where recovery is faster and the diversity of taxa and communities is greater. This is primarily due to greater summer warmth, a major requirement for the growth of erect woody stems and trunks. The relationship between summer temperature and shrub height and cover is reflected in all the major systems dividing the Arctic into vegetation or floristic zones (e.g. Polunin 1951, Cantlon 1961, Andreev 1966, Young 1971, Aleksandrova 1980, Bliss 1981). Throughout the Arctic, shrub tundra does not occur in areas where the mean temperatures in July are less than 7°C, but shrubby willows (for example, *Salix pulchra, S. alaxensis, S. lanata, S. glauca*) play an important role in successional upland communities south of the 7°C mean July isoline. The woody species that do colonize disturbed sites are generally only the fastest growing ones. Rapidly growing willows are able to colonize open sites, whereas birch (*Betula nana*) and ericaceous shrubs (e.g. *Ledum palustre* ssp. *decumbens, Vaccinium uliginosum, Empetrum nigrum*) are not important colonizers.

*Buried seed bank.** Another aspect of recovery that has only recently received much attention in the Arctic is the buried seed bank. Large numbers of native plant seedlings appeared on recent disturbed sites before there was any external seed input (Chester and Shaver 1982, Gartner et al. 1983). These seedlings were concentrated in organic soils, and McGraw (1980) showed that their probable source was buried seed held in the organic layer of undisturbed tundra. McGraw's conclusions were later confirmed in a more extensive analysis by Gartner et al. (1983). The conclusion from these studies was that replacement of organic soils matter after a disturbance was particularly important to native plant recovery because the organic layer contained the principal native plant seed source and because native plant growth rates were higher in organic soils than in mineral soils. Fertilizing adjacent strips of undisturbed tundra may promote seedling establishment, but a dependable strategy for encouraging seed production is not currently available.

The germination strategies of many arctic plants appear to be useful for seedling establishment on disturbances (Densmore 1979, Gartner 1983). The highest germination rates are at high temperatures (25-35°C) and in the sunlight. This indicates that many of these species may be preadapted for colonizing disturbances.

Seedlings survive better on organic soil than on mineral soil. An experiment in which grids of toothpicks were implanted in various substrates showed that the mineral substrate was much less stable than the organic substrate (Gartner et al. 1983). Thus, adding organic matter to an artificial seedbed may increase the success of seedlings by reducing needle ice or other unfavorable physical factors.

Weeds are not important in the buried seed bank, but they were observed at a number of seeded sites (Johnson 1981, Kubanis 1982). These were introduced both in straw mulch and in the seed mix. On the North Slope, weeds generally did not persist. Kubanis (1982), however, noted that there is nothing that prevents weeds from becoming a problem in the Arctic. Numerous weedy taxa have been observed successfully germinating, developing and producing viable seeds within the limited growing season, so some introduced taxa may be able to persist under arctic conditions given open habitat and sufficient numbers of individuals to establish a population.

*Revegetation and restoration**

Severely disturbed sites, such as bladed trails and gravel pads, may require active measures to mitigate disturbances. Revegetation, or the return of a plant cover on a disturbed site, can usually be accomplished quickly with fast-growing agronomic grasses on all but the most edaphically or climatically extreme sites. However, these methods require frequent fertilization to maintain an adequate cover, especially in the Arctic. Restoration, which implies a return of the site to its former undisturbed state, is more difficult and in some cases impossible to achieve. Nonetheless, restoration has become a major goal of revegetation efforts, particularly in northern Alaska, where much of the area is wilderness or has high scenic value.

* Prepared by G. Shaver and B. Gartner.

* Prepared by L. Johnson, G. Shaver and B. Gartner

The development of northern revegetation and restoration techniques has been influenced by engineering (Conwell 1977), agronomic (Lucas 1975) and ecological (Chapin and Chapin 1980) methods. The engineering approaches and, to a lesser extent, the agronomic approaches have brought techniques developed in temperate areas to the Arctic and Subarctic. These include the use of relatively high fertilizer rates, fast-growing nurse crops (Johnson 1981) and commercially available grasses. In contrast, the ecological approach has developed slowly and recently. It relies almost exclusively on plant materials specific to the Arctic and the Subarctic (Mitchell 1979, Chapin and Chapin 1980). This approach emphasizes revegetating with native plant species that are well adapted to natural disturbances (e.g., fire, frost action, landslides) that are analogs of anthropogenic disturbances (e.g., off-road vehicle trails, scraping, burial).

The rapid development of disturbance plant ecology and the recognition of distinct plant life strategies, in the Arctic and Subarctic and elsewhere, has aided the development of ecologically based northern revegetation techniques. Grime (1977, 1979) hypothesized the existence of three primary plant strategies (competitive, stress tolerant and ruderal). This classification helps in choosing plant species suitable for revegetation. For example, ruderal species could provide a rapid vegetation cover but would not be expected to persist as a permanent vegetation. Thus, ruderal species might well be ideal as temporary erosion control covers on unstable sites. In contrast, stress-tolerant species should be used only on stable sites with severe growing conditions such as drought or low nutrient levels. The slow growth of a stress-tolerant species may be acceptable if the species is likely to persist for the long term.

Connell and Slatyer (1977) proposed three models for understanding succession: 1) the facilitation model, where early plant species actually aid the establishment of later species, 2) the tolerance model, in which longer-persisting species can tolerate lower levels of resources, and 3) the inhibition model, where all plant species deter the establishment of other species. These models can also help in planning for northern revegetation. For example, if the inhibition model applies to most arctic revegetation, then only those plant species that are acceptable as long-term vegetation should be seeded on a disturbed site.

Nutrients are critical for arctic and subarctic communities (Tieszen 1978, Brown et al. 1980, Chapin 1980b). Nutrients often limit plant growth because their availability is limited or because nutrient cycling is slowed by low decomposition rates controlled by low soil and air temperatures.

Chapin (1980a) summarized what is known about plant nutrient behavior. Many arctic and subarctic plant species are limited by either nitrogen or phosphorus. To some extent revegetation techniques can reduce nutrient limitation by properly managing the substrate. Fertilization, of course, can provide nutrients directly, but this may only last a short time (Chapin and Chapin 1980). Alternatively, careful management of topsoil can aid both by conserving nutrients and by slowly releasing nutrients over many years (McGinnes and Nicholas 1980, Power et al. 1981). Substrate can also be important for revegetation because of buried seed (Leck 1980, McGraw 1980, Chester and Shaver 1982, Gartner 1982, 1983, Gartner et al. 1983, Fox 1983, Roach 1983).

The need for active measures can be significantly lowered by using less gravel for construction. Material sites and gravel pits covered the most areas of any impact along the TAPS. Any technique that decreases gravel use, such as using insulation to reduce the thickness of drill pads or allowing thinner pads for temporary construction, can decrease the total area affected.

*Fertilizer and artificial seeding effects.** Johnson (1984) reviewed the role of fertilization at revegetated sites. Initially it was thought that heavy fertilization would improve native plant colonization on disturbances. However, fertilization generally increases the abundance of high-turnover species and growth forms, so that grasses and deciduous shrubs become more dominant (Lechowicz and Shaver 1981, Shaver et al. 1983, Shaver and Chapin 1984). The causes of this are numerous. Competition plays a large role; for example, low growth forms are easily overtopped by faster-growing introduced species. Fertilization increases biomass turnover rates significantly within species, by means such as increased tiller turnover (Fetcher and Shaver 1983) or leaf turnover (Shaver 1981). On disturbed sites, fertilization of unseeded areas causes an increase in biomass after four years (Gartner et al. 1983), but there is no effect on the native plant cover or the biomass of artificially seeded areas after ten years (Chapin and Chapin 1980). Fertilization of disturbed sites, however, reduces the number of individual plants, particularly sedges, causing a shift in species composition toward dominance by native and nonna-

* Prepared by L. Johnson.

tive grasses (Gartner et al. 1983). Because fertilization has such a strong effect on species composition with little or no long-term effect on biomass, fertilization may actually deflect the restoration process toward an unnatural vegetation. Fertilization may improve biomass recovery in the first five years on mineral soils, but it may be unnecessary or at least can be reduced on disturbances where an organic soil remains or is replaced.

On tussock tundra sites that are not manipulated artificially, the effects of changes in nutrient availability caused by disturbances are similar to the simple fertilization response of undisturbed tussock tundra. In a preliminary survey of vehicle tracks, the concentrations of nitrogen and phosphorus in the soil and plants and the uptake of nitrogen and phosphorus in plants were much higher in the tracks than in adjacent undisturbed tundra (Challinor and Gersper 1975, Chapin and Shaver 1981). Higher soil temperatures account for some but not all of this difference, suggesting a more fundamental change in nutrient cycles in the track. Recent soil enzymological studies (Linkins, unpublished) and litter bag studies (Shaver and Chapin, unpublished) have shown qualitative differences in nitrogen and phosphorus mineralization and movement in soils of vehicle tracks vs undisturbed sites. The increased nutrient availability in vehicle tracks apparently contributes to the development of nutrient-rich vegetation dominated by graminoids and deciduous shrubs with a high production-biomass ratio. Restoration of old vehicle tracks to a more natural vegetation must be accompanied by a decrease in soil nitrogen and phosphorus availability and nutrient movement.

*Future revegetation eforts.** The lessons learned along the TAPS will be used in future revegetation methc 's (Johnson 1984). Unlike the TAPS efforts, the primary goal of revegetation has now shifted to reestablishment of native plant communities. Since there is increasing evidence of the adverse effects of high seed and fertilizer applications on native plant reinvasion, the extent and rate of seeding should be reduced for nonnative species. Nonerodible areas should receive low levels of fertilizer and no seeds unless the likelihood of natural reinvasion or site recovery potential is low. Site recovery potential is based on the growth potential of the substrate (its ability to provide adequate nutrients and moisture) and the reinvasion potential of the surrounding vegetation (its ability to produce and disperse viable seed into

Table 8. Site recovery potential.

Reinvasion potential	*Growth potential* *High*	*Medium*	*Low*
High	High	High	Medium
Medium	High	Medium	Low
Low	Medium	Low	Low

the site combined with the likelihood of germination from viable buried seeds in stockpiled substrate) (Table 8). To evaluate site recovery potential, research is underway to determine the rate of succession on disturbed sites of varying ages and substrates in each major vegetation region.

The predicted changes in vegetative cover are based on the results of seed mixes of primarily nonnative grasses (Table 9). Within the last five years, three native grasses have been released for Alaskan revegetation (Mitchell 1979), and more will surely follow. Two of these, *Arctagrostis latifolia* and *Poa glauca*, were used to a limited extent within NPR-A; *Arctagrostis* was used in the later stages of the TAPS revegetation. These species should be able to sustain a better cover for periods of 10–20 years because of better adaptation. These mixes will aid in reestablishing native plants both by decreasing the need to use agronomic species and by allowing native vascular plants to reestablish before moss mats form on fertilized areas.

Active seeding will be restricted to sites that are erodible or have low recovery potential. Seeding rates will probably be much lower than used for TAPS. Seed mix application rates evaluated for the proposed natural gas pipeline varied from 1000 to 3200 seeds/m² (6–32 kg/ha), or about 38% of the rates used along TAPS. Several mixes and rates were tested in order to formulate distinct seed mixes for various geographic zones and for sites of different erodibility. Annual ryegrass should only be considered for highly erodible areas. Future seed mixes should be able to rely almost exclusively on native grasses and forbs (Table 3 and 4).

Alternative strategies can be used to accelerate the reestablishment of native species and eventual restoration of sites. Cuttings, seedlings and seeding of willows have been tried with some success along TAPS (Johnson 1981). These should take advantage of the knowledge of plant distributions and growth-form variation with climate and substrate. Experimental cuttings of willow did very well at two sites in the northern Brooks Range foothills, while birch cuttings had only limited

* Prepared by L. Johnson.

Table 9. Revised 1977 seed mixes (kg/ha) used along TAPS (Lucas 1975). Numbers in parentheses are the amounts used in the original 1975 mix.

	Seed mix 1 *North Slope: Sect. 6 (Toolik to Prudhoe Bay)*		*Seed mix 2* *Brooks Range: Sect. 5 (Coldfoot to Toolik)*		*Seed mix 3* *Int.: Sect. 1, 3, 4 (Coldfoot to Valdez except Alpine)*		*Seed mix 4* *Alpine: Sect. 2 (Gulkana to Tanana River)*	
*Arctared fescue (*Festuca rubra*)	12.3	(16.5)	4.5	(16.5)			4.5	(11.1)
*Nugget bluegrass (*Poa pratensis*)	12.3	(11.1)	10.1	(11.1)	5.6	(0)		
Redtop (*Agrostis alba*)	1.5	(5.5)	3.4	(5.5)				
*Boreal red fescue (*Festuca rubra*)	10.1	(5.5)	10.1	(5.5)	101.6	(4.4)	5.6	(4.4)
Durar hard sheep fescue (*Festuca ovina* var. *duriuscala* L.)			10.1	(0)		(4.4)		
Climax timothy (*Phleum pratensis*)			4.5	(5.5)	2.2	(0)		
Meadow foxtail (*Alopecurus pratensis*)			11.2	(5.5)	6.7	(13.2)	12.3	(11.1)
Sydsport bluegrass (*Poa pratensis*)						(3.3)	14.6	(5.5)
Manchar brome (*Bromus inermis*)					10.1	(5.5)	2.2	(0)
Annual rye (*Lolium multiflorum*)	14.6	(16.5)	13.4	(16.5)	7.8	(11.1)	7.8	(11.1)
†Tall arcticgrass (*Arctagrostis latifolia*)	1.1	(0)						
Total	51.5	(55.1)	67.3	(66.1)	43.6	(41.9)	47.0	(42.2)
Seeds/m^2	5600	(7500)	7700	(8600)	3100	(2600)	5200	(3400)

* Varieties of native taxa.
† Native on the North Slope.

success. Tussock sedge (*Eriophorum vaginatum*) sodding reestablished 70–90% of the time on moist sites (Johnson 1981). Unfortunately these techniques have not been attempted on a large scale, and their cost will deter widespread use unless alternative procedures can be developed.

Gravel roads, gravel pads and sites with coarse gravels present special problems. Because construction surfaces are drastically changed, through either burial or removal of the vegetation and its underlying organic layer, these sites will not be restored within 20–30 years because gravels provide little water or nutrients for plants. But a functioning plant community may develop within this time if careful revegetation measures are taken. These include stockpiling and respreading organic and fine-grained materials over the pad or road site prior to seeding or planting. These materials not only improve the moisture and nutrient characteristics of the substrate, but they also provide viable seeds, roots or rhizomes that promote rapid reestablishment of native species. Some disposal sites along the TAPS demonstrated this potential (Johnson 1984). Fertilizing at moderate levels (50 kg/ha of nitrogen, phosphorus and potassium), seeding or transplanting native plants, and using the appropriate engineering measures to ensure the stability of the site also promote site recovery.

Biological measures alone cannot always allow a site to recover. It may be necessary to use engineering measures, such as drainage control, to help stabilize a site, particularly in areas with high ice content. Revegetation can then be successful in further stabilizing the site and accelerating recovery.

Cumulative impacts*

In recent years we have come to recognize that large oil fields and long pipelines create fundamentally different ecological concerns than those resulting from the early oil exploration. Past dis-

* Prepared by D.A. Walker and P.J. Webber.

turbances were not as frequent, as intense nor as large as those of today. The argument that the Prudhoe Bay region is only a small portion of an inexhaustible and extensive wildlife resource is no longer tenable since it is now clear that the Prudhoe Bay and Kuparuk fields are the forerunners of a vast network of oil fields.

Environmental protection legislation requires that environmental impact statements (EISs) address the issue of cumulative impacts (Council on Environmental Quality 1978). However, very few EISs deal with the problem adequately because the understanding and methods needed to make the assessment are largely lacking. A recent analysis sponsored by the U.S. Fish and Wildlife Service (Cline et al. 1983) regarding the state of the art of cumulative impact research concluded:

> "The methods which have been used... are inadequate to determine the cumulative impacts of large-scale projects. Assessments have focused on limited types of impacts, with a heavy reliance on physical parameters, relating the impacts to the biotic community only as a last step.... Interaction and synergism, to some extent the essence of cumulative impacts, have been largely ignored."

Although a comprehensive approach for examining cumulative impacts is not available, there have been many research projects and workshops devoted to developing satisfactory solutions to this problem (for examples, see Horak et al. 1983 and Cline et al. 1983). Horak et al. (1983) described the approaches that have been used in the past. One approach is called the "exploratory" or "extrapolative" approach. In exploratory forecasting, trajectories of present development patterns are emphasized. The first step toward predicting the future effects of developments is to study the history of disturbances that have already occurred. Maps are useful for this, especially if imagery shows the gradual evolution of major areas of development and the consequent impact on the terrain.

Since 1970, CRREL has sponsored several mapping research programs in northern Alaska (Carey 1972, Everett 1975, 1979, Webber and Walker 1975, Everett and Parkinson 1977, Komárková and Webber 1978, 1980, Everett et al. 1978, Walker et al. 1980, 1982, Walker 1983, Walker and Acevedo, in press). Landsat mapping in the Arctic National Wildlife Refuge (Walker et al. 1982) and the Beechey Point Quadrangle (Walker and Acevedo, in press) and geobotanical mapping at Prudhoe Bay (Walker et al. 1980) led to the development of a hierarchical classification system that permits cross referencing of Landsat-derived vegetation units with vegetation classes of photo-interpreted maps at larger scales. The latest approximation of a classification (Walker and Acevedo 1987) has evolved from numerous earlier studies in northern Alaska (Lent and LaPerriere 1974, Belon et al. 1975, Nodler and Laperriere 1977, Lyon and George 1979, Morrissey and Ennis 1981) and at the Landsat level is similar to the Alaska statewide land cover classification.

Cumulative impact analyses often require more information than can be obtained from Landsat data. Automated mapping techniques permit a wide variety of detailed information to be integrated into a single data base. Such data bases, termed geographic information systems (GISs), can incorporate any information that can be displayed on a map, including topography, geobotanical information, cultural features and terrain changes associated with development.

Geobotanical information and historical disturbance information have recently been combined into a single data base for examining cumulative impacts for the Prudhoe Bay oil field (Walker et al. 1986). The geobotanical portion of the data base contains detailed (1:6000-scale) information for vegetation, soil, landform, surface form and percent water cover. The historical disturbance portion of the data base includes time series maps of natural and anthropogenic changes to the landscape, including lake and river boundary changes, roads, pads, flooding, thermokarst and debris. A variety of maps can be made from the data base, including maps of a single geobotanical attribute (vegetation, soil, landforms); maps of historical stages of development (Fig. 34); and maps based on complex models using numerous attributes in the data base, for example, tundra resistance to damage by off-road vehicles.

Geographic information systems are powerful tools for analyzing the effects of disturbance on the natural landscape. For example, the following conclusions were derived from the analysis of the Prudhoe Bay data base:

- The size of the Prudhoe Bay road network and gravel-covered areas has grown linearly between 1968 and 1983 and now includes about 350 km of gravel roads and 2150 ha of gravel roads and pads (Fig. 35). The Kuparuk field has grown at a similar rate between 1978 and 1983.
- The roads within a heavily developed portion (21 km^2) of the oil field reached a maximum density within a few years, but the area covered by pads and the total gravel placement continued to grow linearly.

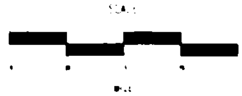


Figure 34. Anthropogenic disturbance in 1970 and 1983 for a 22-km² area in the Prudhoe Bay oil field.. These maps were prepared from the North Slope Borough's geographic information system. The Prudhoe Bay data base covers three areas of this size and consists of 19 components: 10 geobotanical variables, 3 years of natural disturbance information and 6 years of anthropogenic disturbance information. (Modified from Walker et al. 1984.)

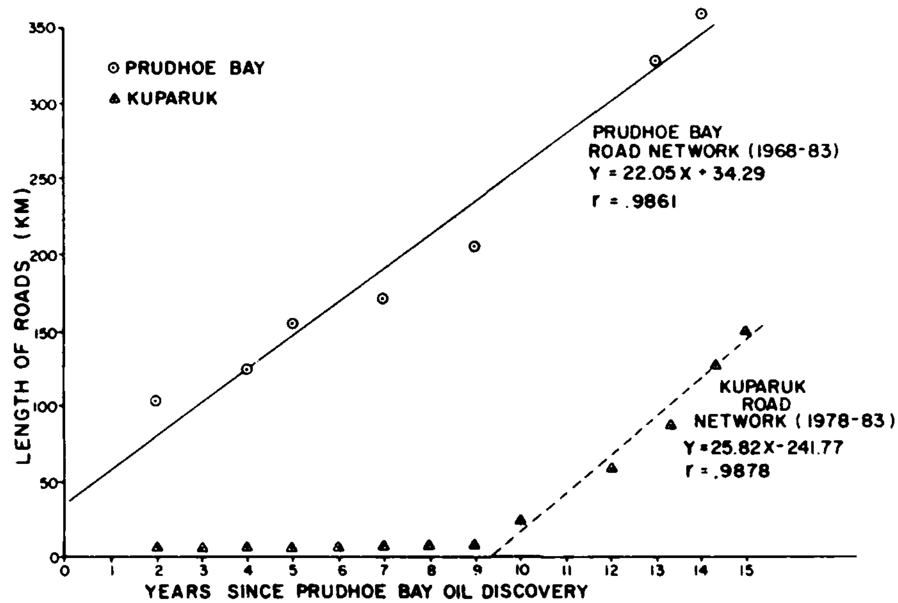
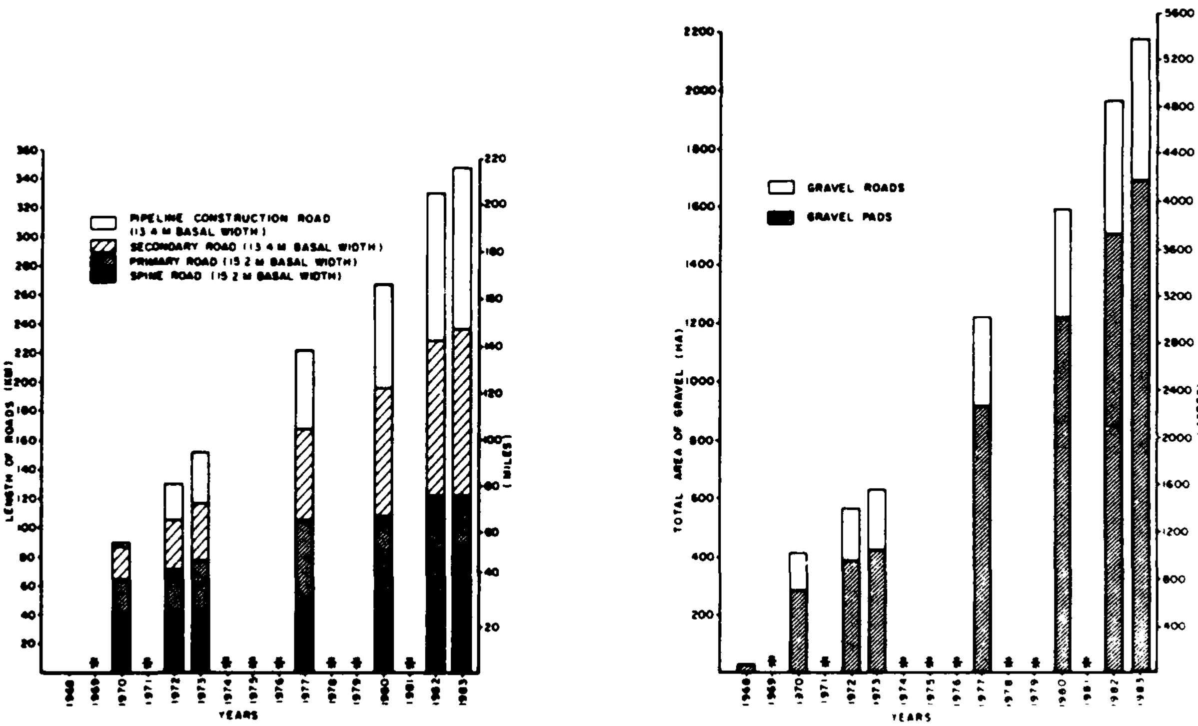
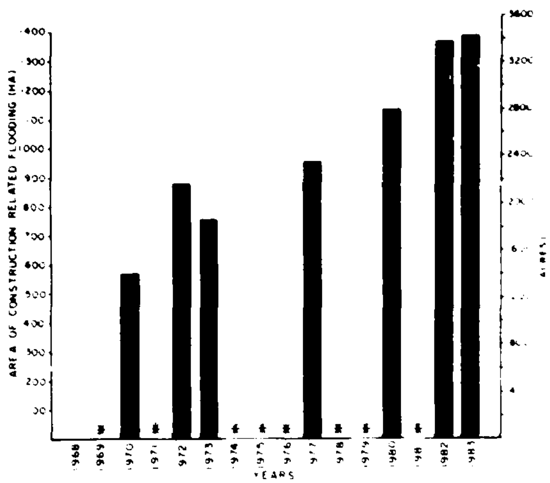


Figure 35. Comparison of the growth of the Prudhoe Bay and Kuparuk oil field road networks. The top line is for the Prudhoe Bay road network since the discovery of oil in 1968. The bottom line shows the growth of the Kuparuk road network since 1978, when development began to expand.



a. Total road length. *b. Area covered by gravel.*

Figure 36. Historical impacts in the Prudhoe Bay oil field. Starred columns are years of missing or incomplete data. (Modified from Walker et al. 1984.)



c. Impoundments.

Figure 36 (cont'd). Historical impacts in the Prudhoe Bay oil field. Starred columns are years of missing or incomplete data. (Modified from Walker et al. 1984.)

- Within the same heavily developed area, indirect impacts of thermokarst showed an exponential rate of growth (Fig. 36), and the total area covered by the indirect impacts of thermokarst and flooding was more than double that of the primary impact of gravel placement.
- The magnitude of indirect impacts depends considerably on the type of landscape affected and the density of roads and pads.
- Different disturbance types affect the various geobotanical units differentially. For example, on the flat thaw-lake plains, moist and dry sites tend to be selected for gravel placement, whereas anthropogenic impoundments occur primarily in the naturally wet or aquatic tundra types. These disturbance distribution patterns have important implications for wildlife.

Case studies such as the one at Prudhoe Bay are an important phase in the development of useful methods for evaluating cumulative impacts (Horak et al. 1982); these methods will be fruitful for predicting the pattern and effects of future developments. As Horak et al. (1982) concluded in their cumulative-impact guidance manual:

> "A good strategy at this point is to concentrate on case studies in order to illustrate current challenges, on-going practices and how pragmatic questions are answered in the field. In the context of realistic problems, it may be easier—inductively—to arrive at agreed upon procedures. Operational models need to be developed through interdisciplinary and interagency planning and funding. The cumulative issue is too large for one agency to efficiently and effectively manage."

RECOMMENDATIONS

The fate of the Alaskan North Slope depends on our commitment to protect its extraordinary environmental resources. We are currently witnessing the rapid transformation of the region from a wilderness to a vast complex of resource extraction areas. The environmental quality will be protected only through enlightened engineering designs and sound environmental legislation that depend on the results of research such as that which CRREL has sponsored in the past. The exploration of NPR-A, the oil-field development at Prudhoe Bay, and the construction of the trans-Alaska pipeline led to many innovative approaches to minimizing direct environmental damage (National Research Council 1983, Alexander and Van Cleve 1983). However, as we have emphasized in this report, the scale of development now requires a shift in emphasis toward cumulative impacts. We probably have seen just the beginning of extensive large-scale development in northern Alaska, and continued research is needed to minimize future impacts. The following list of recommendations is divided into two parts: integrated research programs, and extrapolation and application of research results to the planning process.

Integrated ecosystem studies

Integrated research, in particular the research at Cape Thompson (Wilimovsky and Wolfe 1966) and Barrow (Tieszen 1978, Brown et al. 1980), has been an extraordinarily successful way to achieve a basic understanding of the coastal tundra ecosystem. These programs accomplished a great deal, but there is still a need for detailed process-level studies to help explain the reaction of tundra to disturbance. In particular, why are disturbed sites so productive and apparently nutrient rich, especially if they are wet? Nutrient availability is one of the most important keys, but we know very little about what actually causes this. Is it increased decomposition or is it because increased thaw and slumping of the permafrost create a nutrient sink for inputs from the surroundings? Is the total amount of mineralized nutrients greater on disturbances, or is the higher productivity due primarily to greater nutrient mobility? In the foothills there is a need for research regarding the complex interactions involved with nutrient and

water transport on slopes underlain by permafrost. A recently established Department of Energy research program (Response, Resistance, Resilience and Recovery from Disturbance in Arctic Ecosystems) is examining some of these questions (Oechel 1986), and other large-scale and long-term experiments involving disturbances of entire watersheds should be considered to examine the consequences of disturbing large areas by strip mines, fires and large toxic spills.

River flood plains are the most important tundra areas with respect to nutrient exchange, high plant productivity and wildlife use, and these are the first areas impacted for recreation, gravel resources and utility corridors. Most of the planned oil fields and corridors will impact flood plains and deltas in some way, and we critically need basic ecosystem information from these areas. Other information gaps are in the foothills and mountains, where roads and mining are likely to occur as these areas become more accessible. Basic ecological research is needed regarding successional processes, hydrological and erosional processes, the relationship of flood plain disturbances to wildlife, and the resistance and resilience of flood plain ecosystems to common disturbances. We need to examine the differences in disturbance and recovery processes in different climatic regimes, in acidic and alkaline tundras, and in regions with differing surficial geology.

We still have only a rudimentary understanding of common successional processes in northern Alaska. Such studies would be enhanced by the application of recent theories of patch dynamics (e.g. Pickett and White 1985) to natural and anthropogenic tundra disturbances. In addition to the successional story along rivers, basic research is also needed regarding the thaw lakes of the coastal plain, including the conditions required for initiation and growth of thaw lakes, the succession of vegetation communities, the development of thaw bulbs beneath lake basins, the redevelopment of massive ground ice in drained lakes, and the history of thaw lakes. Examination of succession on isolated dry barren areas away from rivers would undoubtedly aid revegetation efforts of abandoned roads and pads.

Techniques are needed for tundra ecosystem restoration, in contrast to merely reestablishing a vegetation cover. More research is required on the mechanisms of native plant establishment on mineral vs organic substrates. Native and introduced grasses tend to do much better on mineral surfaces, but the dominant tundra species do best in organic soil. The implications of this pattern are important for revegetation management. Differences due to temperature and moisture regimes, and especially nutrient availability and soil stability, need to be explained. Revegetation techniques need to incorporate more native species (and not necessarily grasses) into the seed mixes. Special seed mixes and new revegetation techniques are needed for the most extreme sites.

Methods of extrapolating experimental information

One of the biggest challenges facing investigators is how to make the wide diversity of experimental research useful to planners and managers. We need methods of extrapolating experimental information to broad regions of the North Slope. Geographic information systems hold much promise for this, but experiments need to be designed with extrapolation as one of the main objectives. In particular, experiments should be replicated in as many of the GIS vegetation and terrain units as possible. The techniques require the map information and scale to be appropriate for a given experiment. There are, however, great dangers of overextrapolation in areas where our ecological understanding is incomplete or where the terrain is mapped inaccurately or at an inappropriate scale.

To facilitate the application of GIS technology, the North Slope needs to be mapped according to consistent ecological units (vegetation, surface forms and terrain units), whereby disturbance and recovery information from one part of a unit can be applied to other similar areas. This should be done at scales appropriate for both regional planning (1:250,000) and site-specific planning (1:6000). A series of permanent test sites should be established in the major landscape units where replicate long-term disturbance experiments could be conducted and monitored without interference from ever-expanding human activities.

The existing oil fields are other long-term "landscape experiments" that we should take advantage of, particularly because some of the most critical problems are related to the accumulated and possible synergistic effects of multiple impacts. We can draw much insight from case studies for extrapolation to new oil fields, and we hope a comprehensive approach for examining cumulative impacts can eventually be developed. The cumulative impact methods developed so far are primarily for disturbances of vegetation communities, but they also need to be applied to problems related to wildlife populations. One approach is

through habitat models based on the existing geobotanical information.

Our ability to monitor resource developments and accurately assess environmental sensitivity across large tundra areas could be improved with advances in remote sensing. Particularly needed are methods of mapping ground-ice volumes. Data that specifically relate ground ice to basic geobotanical units would be particularly useful for mapping terrain sensitivity and engineering suitability. Information from the many auger holes made during placement of elevated pipeline pilings would provide valuable subsurface ground truth across broad regions.

These recommendations are only the beginning of the challenges for the next few years, but in general they represent an integration of the key concepts of protecting the vegetation because of its importance to landscape integrity and wildlife, understanding the limitations that permafrost and the unique physical environment of the Arctic impose on recovery, and recognizing the critical role that environmental research plays for developing engineering and planning tools to protect these resources.

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APPENDIX A: DIRECTLY FUNDED AND COOPERATIVELY CONDUCTED PROJECTS

Vegetation mapping and response to disturbance along the Yukon River-Prudhoe Bay Haul Road	P.J. Webber, V. Komárková, D.A. Walker and E. Werbe, University of Colorado
Distribution and properties of road dust and its potential impact on tundra along the northern portion of the Yukon River-Prudhoe Bay Haul Road	K.R. Everett, The Ohio State University
Botanical reconnaissance of the Yukon River-Prudhoe Bay Haul Road and in NPRA	D.M. Murray and B. Murray, University of Alaska, and A.W. Johnson, San Diego State University
Investigations of weeds and weedy vegetation along the Yukon River-Prudhoe Bay Haul Road	A.W. Johnson and S. Kubanis, San Diego State University
Geobotanical mapping and environmental assessment in northern Alaska	D.A. Walker, P.J. Webber, University of Colorado
Ground ice distribution, formation and terrain degradation in NPRA	D.E. Lawson, CRREL
Soil-landform interactions in wet arctic and alpine tundras along a regional climatic gradient	K.R. Everett, The Ohio State University
Effects of latitude and climatic variation on arctic plant growth	G. Shaver, Marine Biology Laboratory
Revegetation of Alaskan disturbed sites by native species	F.S. Chapin III, University of Alaska, and G. Shaver, Marine Biology Laboratory
Latitudinal and altitudinal climatic gradients in north central Alaska	R.K. Haugen, CRREL
Assessment of revegetation techniques used along the haul road and in NPRA	L. Johnson, CRREL, Fairbanks
Long-term effects of off-road vehicles in NPR-A	G. Abele, CRREL
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A facsimile catalog card in Library of Congress MARC format is reproduced below.

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Disturbance and recovery of arctic Alaskan tundra terrain: A review of recent investigations / by Donald A. Walker, David Cate, Jerry Brown and Charles Racine. Hanover, N.H.: U.S. Army Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1987.

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